Opening the Black Box:

Cognitive and Interpersonal Mechanics of Knowledge Interactions in Interdisciplinary Collaborative Teams

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Lianghao Dai
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First assessor: Prof. Dr. Margarete Boos

Additional supervisors: Prof. Dr. Regina Bendix

Prof. Dr. Karin Kurz

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Summary

This doctoral dissertation teases out how scientific knowledge in interdisciplinary collaborative teams is learned, shared and integrated in scientists' minds and in their daily interpersonal communications. This work is based on thirty months of ethnographic fieldwork conducted at a German university between the years of 2012 and 2016. In total, seven interdisciplinary collaborative projects with thirty-seven scientific researchers have been investigated. Deploying methods of participant observation, semi-structured interview and cognitive mapping, this research visualises and analyses personalised and structural understandings on knowledge among members of interdisciplinary collaboration and their division of labour, a cognitive and interpersonal process which for a long time scholars in the sociology of science and in the Science of Technology Studies were unable to clearly capture and illustrate. This doctoral dissertation thus makes a critical contribution to these fields by innovatively combining methods of cognitive mapping and social network analysis to help understand the cognitive and interpersonal mechanism of knowledge production and innovation.

To be more specific, it claims the following main findings:

(a) Shared knowledge between scientists is established via processes of contextualisation and integration. The necessary extents and structures of shared knowledge for building up an interdisciplinary research team differ depending on two collaborative patterns: theory-method pattern and technical pattern.

(b) In an interdisciplinary collaborative team, the discipline a scientist belongs to merely influences the strength of cognitive connections. But the hierarchical position one is located affects not only that but also the rhythm that a pair of scientists work interdependently. There is a clear division of labour between the junior and senior researchers in a team. Junior researchers conduct practical and technical works asynchronously in a 'zip process'; seniors take care of general ideas and work on the same pace during the networking process. Groups of a senior and a junior from the same disciplines interact in the knowledge plantation mode.

(c) A quadruple-people team with one senior and one junior researcher from each of the two disciplines have been found with higher work efficiency than a team with four seniors from the same two disciplines, if the junior is well-trained and experienced in operations related to the project. As well, the effectiveness of an interdisciplinary research, that leads to knowledge innovation, is achieved by two modes of division of labour.

(d) A sharing of knowledge has to be achieved in order to build up an interdisciplinary collaborative team, but it cannot guarantee the maintenance of the team. Thus this dissertation argues that the interpersonal networks of scientists are based on the network of scientific notions baring in scientists' minds, namely the former is embedded into (Granovetter, 1985) the latter.

Based on these findings, this dissertation provides a number of policy recommendations for better enhancing the performance of interdisciplinary collaboration projects and for evaluating the quality of the collaborative endeavour in the scientific academia.

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Chapter One

An Introduction to Interdisciplinary Scientific Knowledge Interaction

1.1 An Ethnographic Glimpse of an Interdisciplinary Project

'*Here it is!*' Leo, a young biologist postdoctoral researcher, excitedly pointed to the microscope screen, on which appeared a clear image of a Drosophila embryo, the maggot of a fruit fly. [1] '*How cool it is!*' I agreed.

This conversation took place when I was invited to visit Leo's laboratory for the first time. The laboratory was located in the basement of the building, which was two floors down from his office. In the laboratory, there was a microscope room, which was designed to be extremely dim for scientific observation. Because the microscope screen was on, I could see the electronic microscope Leo used to conduct his experiments. In addition to this microscope, there was a set of shelves and a refrigerator. After a brief introduction, Leo picked up some samples of Drosophila embryo, which were arranged on a transparent slide from a dry box on the shelf, and carefully loaded them into the microscope. He then set up several parameters on a special software program that controlled the mirrors and signal collection process of the microscope. Eventually, images of these samples clearly showed up on the screen linked to the main body of the microscope. Displayed on the screen was an oval-shaped object containing hundreds of little points that twinkled like stars. But unlike the stars in the sky, they were distributed in a special order. '*This is the embryo of a fly, and these shining points are nuclei of the embryo.*' Leo explained, '*Every five seconds the computerised microscope takes a picture of the embryo. Then after 20 minutes I will have a video of how it develops.*'

Suddenly, on the left side of the embryo, several nuclei divided into two identical ones. One by one, from the left to the right, every nuclei of the embryo was doubling. After all nuclei had finished their division, an oval shape with denser points showed up. The whole process looked like a 'wave of doubling' from the left to the right side of the oval.[2] '*This is the mitotic wave in the early stage of Drosophila embryonic development, which is called the T1 process. Finding out the mechanics of this wave is our goal at this stage of research*' Leo continued.

Leo's work constituted only a small part of a larger interdisciplinary collaborative project. The purpose of this larger project was to discover the mechanics of mitotic wave in the T1 process. The task of biologists involved in this project was to understand how certain development processes of tissues or embryos unfold. One of their main research results was the collection of a complete video recording that illustrated the essential T1 stages of embryos development. The

[1] Names of people and the university where I conducted my fieldwork for this thesis have been anonymised for privacy protection.
[2] An example of the video of the mitotic division wave can be seen on YouTube: https://youtu.be/-Nf6CyWNodA by rajutomer on Jun 5, 2012.

biologists then passed the data onto the statisticians, whose expertise lay in the 'statistical translation' of the video data. The statisticians would analyse the video data and interpret the sets of images into numeric form with the help of computer programs. With these sets of numbers, they were able to build theoretical models that could be generated into suggestive indicators, providing further guidelines for the biologists to conduct another round of experiments to test the validity of the model proposed by the statisticians. This collaborative process would go on for several rounds until the models matched the biological data perfectly.

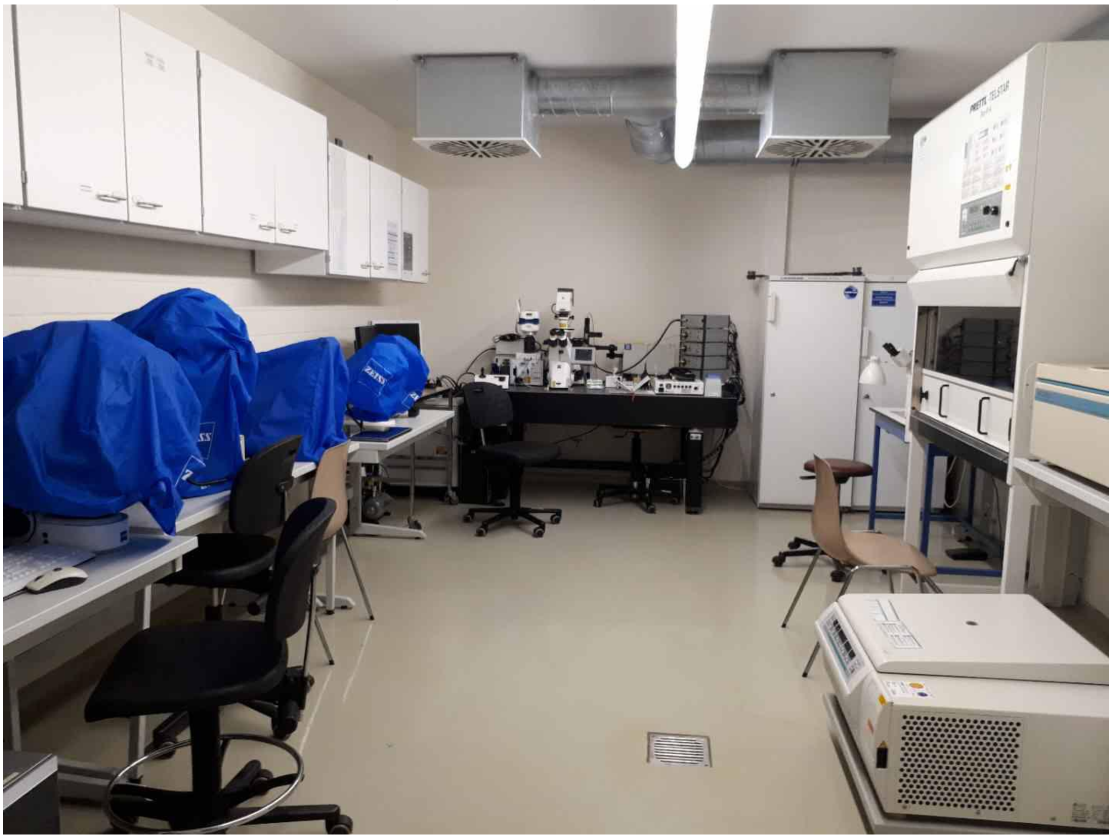

Figure 1.1 Leo's microscopy room with microscopes covered by blue clothes. Photographed by Peter, one of my research informants.

The goal of an interdisciplinary collaborative project like the one Leo and the statisticians took part in would be to achieve a comprehensive story describing an innovative breakthrough in the understanding of a specific question or in methodology from a string of experiments and modelling conducted cooperatively by more than one field. To approach such a goal requires common grounds of some sort for basic foundation of the collaboration; it equally demands distinctiveness of expertise of each collaborative discipline involved for the innovation, which by definition could not have taken place in a conventional knowledge production process within a single field.[3] Once a comprehensive story is achieved, the results would be published in an academic literature platform such as peer-reviewed journals, project reports and books, as well as presented at conferences and workshops. The choice of the platform for such dissemination of new

[3] The requirements of both common grounds among disciplines and distinctiveness of each participant discipline in an interdisciplinary project have been discussed under different names by prior works. For example: a tension between sharedness and uniqueness (Lewis, 2003; Lewis and Herndon, 2011; Ren and Argote, 2011; Kotlarsky, van den Hooff, and Houtman, 2015; Dai and Boos, 2017) or coherence and heterogeneity at the same time (Laudel, 1999)

knowledge would depend on the expertise and experience of the interdisciplinary participants as well as the disciplines involved in the collaboration. A new cycle of knowledge production would then start once new funds were successfully secured and new research interests emerged.

That said, the typical interdisciplinary collaborative process goes far less smoothly. As the saying goes, the devil is in the detail. '*Everyone says that we need interdisciplinary collaborations. Yet, in fact, it is very hard and very time-consuming*' said Leo on his way back to his office after he finished his experiments. '*There are always communication problems both between individuals and between groups. Sometimes I even wanted to quit and just run experiments by myself when it seems totally impossible for participants of the project to simply understand each other*' he complained. '*However, you would be too young – even too naive – if you believe what happens next will go smoothly, even after you and your collaborators seem to have reached a common understanding to basic scientific languages.*' Indeed, to understand each other was one thing, but to work together was another. '*Sometimes, I could not blame my collaborators for being lazy, but I really did not know why it took them months to finish very simple tasks, which I assumed would be completed within one week. The work progress will be much slower when my boss and I, or my collaborator's boss and my boss, do not agree on each other's ideas. This disagreement will double my workload. Well, of course, when the research result comes out, I know that we will never make it by using the biological approach alone. Yeah, interdisciplinarity always provides deeper understandings*' Leo admitted.

1.2 The Research Question

The ethnographic vignette described above is derived from my doctoral fieldwork, which is about the interdisciplinary collaboration (hereafter IDC) among a number of natural and social scientists at a German University from 2012 to 2016. Based on thirty months of fieldwork, this dissertation endeavour to investigate how scientists understand the scientific knowledge they are concretely and practically interacting with, namely the knowledge that is learned, shared, integrated and co-produced within IDC projects. In an IDC project, this kind of knowledge interaction is taking place in people's minds and through daily interpersonal communications consisting of various academic scenarios such as discussions, supervisions, seminars, group meetings and conferences. The goal of this study is to understand the cognitive and interpersonal mechanics of knowledge interactions in the context of IDC. In doing so, this research suggests new theoretical insights on how knowledge structures are related to research team structures. It also proposes potentially convincing practical approaches for enhancing the performance of interdisciplinary collective projects. Before going further into more detailed sub-questions, it is crucial to carefully define key concepts of the whole thesis and to fully discuss both theoretical and practical backgrounds of this study.

1.3 Defining the Interdisciplinary Collaboration

As ambiguous, complex and even sometimes misleading that multiple researches in the broad name of 'interdisciplinary' may seem, it is necessary to state a clear definition of what IDC means in the context of this thesis as well as clarify the range of my analytical radar.

Generally speaking, interdisciplinary collaboration occurs when scientific knowledge is exchanged and integrated among groups of multidisciplinary participants. Put differently, in order to solve scientific problems, IDC participants need to borrow or adapt perspectives and methods (Maton, Perkins and Saegert, 2006). An IDC project requires scientists who bare different sets of scientific knowledge, methodology and epistemology and who follow different research traditions in their fields and organise their research in different ways to work together (Stokols et al., 2003; Tress, Tress and Fry, 2007; Dai and Boos, 2017). However, they might not be able to work as effectively and productively as they assume, as it calls for a lot of efforts to make each other understood and work as a team.

Based on various criteria, IDC can be divided into different categories (van Dusseldorp and Wigboldus, 1994; Krott, 1996; Defila, et al., 2006; Klein, 2010; Defila and Di Giulio, 2015). It can be a very simple communication between a few disciplines that share ‘similar methods, paradigms and epistemologies’ (Klein, 2010: 18), which is generally called ‘the Narrow Interdisciplinary’, or a Wide/Broad one, which is more complex because it usually involves disciplines that seem to have nothing in common and are not compatible with each other[4] (van Dusseldorp and Wigboldus, 1994; Kelly, 1996; Newell, 1998). In my research, both Narrow and Wide/Broad IDC cases have been examined. This thesis concerns not only the collaborative work among natural sciences, including physics, biology, statistics, computer science and medical science, but also the interaction between natural sciences and social sciences such as sociology and social psychology. Despite tremendous internal differences among these disciplines, it should be noted that all the disciplines under study fall in the general category of ‘positive’[5] sciences of one or another (sciences based on empirical data), sitting in contrast to disciplines that rely less on empirical research, such as theoretical physics or math. Also, no cases from the humanities are considered.

IDC can be counted as one kind of cross-disciplinary research activities, which can occur in diverse organisational modes. A typical form is project-based research in which scholars of various scientific backgrounds come together to work in specific projects while remaining committed to their particular disciplinary knowledge production. Other modes include ‘interdisciplinary communication’, in which a multi-disciplinary centre provides an intellectual space to forge dialogues (Krohn, 2010), or new research fields like biochemistry, structural sciences, science and technology studies, and biomimicry emerged from interdisciplinary efforts (Burggren et al., 2010; Schmidt, 2010). Even some institutions and universities have diverged from their traditional disciplinary based department structures and established new interdisciplinary divisions (Sá, 2006), for instance the Max Planck Institute for Biophysical Chemistry in Germany and the Santa Fe Institute in New Mexico, USA. Area studies can also be interdisciplinary, in the sense that scholars working on a specific area on the globe may seek out various disciplines for theoretical and methodological insights. However, a centre of area studies may present itself as a multi-disciplinary research centre as a whole, but each scholar trained in a

[4] Other ways of categorising IDCs include four ways of integrating findings into a synthesis (Defila and Di Giulio, 2015), three kinds of attributes of diversity (Rafols, 2007), and in a more general sense of scientific collaborations, five types of constructing collaboration (Laudel, 2001). None contributes additional detail for clarifying types of IDCs examined in this thesis.

[5] ‘Positivism’ (as it applies to science) was formulated by the first philosopher of science, Auguste Comte, founder of the academic discipline of sociology. See Comte, A. b (1974 reprint). *The positive philosophy of Auguste Comte freely translated and condensed by Harriet Martineau*. New York: AMS Press. (Original work published in 1855, New York: Calvin Blanchard, p. 27.b)

specific research background may only conduct research that belongs to a specific sub-field of a discipline, thus conducting 'sub-disciplinary' research (Klein, 2010).

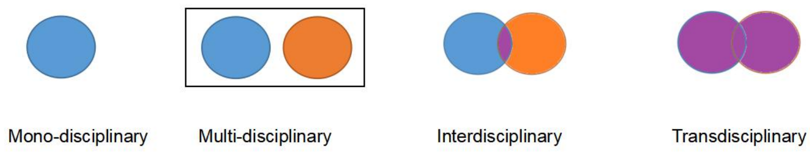

Figure 1.2 An example to differentiate mono-disciplinary, multi-disciplinary, interdisciplinary and trans-disciplinary research

Often interchangeably used in academia, concepts of interdisciplinarity, multidisciplinarity and transdisciplinarity differ from each other in terms of their degree of knowledge integration. In contrast to interdisciplinary collaboration, in which disciplinary boundaries at least partially remain, multidisciplinarity is defined as 'an approach that juxtaposes disciplines…in which disciplines remain separate, disciplinary elements retain their original identity, and the existing structure of knowledge is not questioned' (Klein, 2010: 17). Klein further explains that transdisciplinarity is defined as 'a common system of axioms that transcends the narrow scope of disciplinary worldviews through an overarching synthesis' (Klein, 2010: 65). A vivid example of the differences among these concepts is illustrated in Figure 1.2. My research and the thesis I present here are only concerned with interdisciplinary collaboration in the strict sense of 'inter'. For this reason, no IDC in area studies was investigated. All the researchers I interviewed and/or observed, apart from their interdisciplinary collaborative work, continue to work on their own disciplinary research, and no new disciplines emerged from the collaboration. In this vein, scientists who work alone by integrating knowledge from multiple disciplines on their own are beyond my research radar.

This thesis focuses on interdisciplinarity in the team mode rather than in the single person mode. To further clarify my research scope, only project-based IDC teams taking place over months or years of academic activities, rather than workshop-based IDC teams lasting no more than three days (Heemskerk, Wilson, and Pavao-Zuckerman, 2003; Wesselink, 2009), are considered in this thesis. It is also worth of noting that this thesis investigates IDCs conducted in a single German university, which will be further elaborated upon in section 1.6.1 and Chapters Five. Though many IDC teams are established across universities, cases in this thesis are selected from one comprehensive university for reasons explained in sections 1.5.1 and 1.6.1.

1.4 Practical Backgrounds

The literature reflects that IDC has taken a significant role in today's academic research. The need for interdisciplinary dialogue and collaboration appeared as soon as 'disciplines' were established. By sharing and transferring of knowledge, skills and techniques, IDC can trigger irreplaceable scientific insights and nurture new intellectual companionship (Katz and Martin, 1997). However, IDC was not fully recognised as an inseparable part of academic knowledge production until the 1970s. In this section, three practical necessities of studying IDCs are discussed in context of the Euro-American academic world, which sets up the main backgrounds of this doctoral research.

First, a sound increase of both number and impact of interdisciplinary works has appeared during the last half century (van Noorder, 2015). This is based on the number of articles including ‘interdisciplin…’ in their titles, which has grown to around 2.5 times in the social sciences and nearly 2 times in the natural sciences compared to the literature at the onset of the new millennium. Also, even though interdisciplinary papers are cited less often than disciplinary ones in the three years after being published, they are more popular after over thirteen years of being published. Similar phenomena have been found not only in general, but also in various specific research fields. In library science and information science, the number of research articles that are both co-published by interdisciplinary groups and cited as references by other disciplines have grown over the last decades (Huang and Chang, 2011; 2012). In the area of landscape research, funding agencies and research policy have increasingly favoured IDC projects (Tress, et al., 2007).

The second practical necessity of studying IDCs lies in its potential for solving the tension between trends of mono-disciplinary and of trans-disciplinary research caused by new evaluation systems of scientific works. In the early 1990s, governments in both Europe and the States began to shift their way of public funding management from a policy-oriented, development focused, centralised governance system to a self-regulated, cost-cutting decentralised governance system. The latter was designed to make every performance measurable (Lynn Jr, 2006). In this system, academic funding as well as personal career promotions are formulated to prefer scientists who conduct both comparatively higher quality and higher quantity of scientific works. The logic flaw of this system is that the *quality* of their works is now measured by a ranking system based on the *quantity* of citation of publications, such as the H-index, which has turned scientific publications into academic capital (Ziman, 2000; Clark, 2006).

An intense, higher competition of publication and promotion have been triggered by this system, indicated by the ever increasing number of academic journals and of articles being published in these journals, as well as the growing length of each article (de Solla Price, 1963; Larsen and Von Ins, 2010; Evely, et al., 2010; Bommann and Mutz, 2015). On the one hand, this kind of competition seems to encourage trans-disciplinary collaborative efforts with boundaries of traditional disciplines blurred when researchers take a leading position in the evaluation system by involving new ideas and conducting innovative works. Indeed, trans-disciplinary collaborations are believed to be able to generate publications solving research problems of higher complexity and with deeper insights compared with mono-disciplinary-based studies (Katz and Martin, 1997; Derry and Schunn, 2005; Häussler and Sauermann, 2016). On the other hand, it also thickens the boundaries dividing disciplines because scientific works are only valued in certain journals by certain disciplines in which peer reviews by academic communities are able to take place. It appears the concept of ‘publish or perish’[6] remains a central rule in academia even today (Clark, 2006). Due to this policy, some say scientists have transformed from scholars into academic entrepreneurs who produce scientific papers to pursue higher numbers of publications and citations in a Fordism rationalisation of standardised mass production (Waters, 2004). But because the critical need of publication in discipline-based journals and conferences within the disciplines remains, collaborative projects that involve more than one discipline push research that is trans-disciplinary in nature back to a mono-disciplinary outlook. Consequently, more and more academic researches become neither trans-disciplinary nor mono-disciplinary, but interdisciplinary. Researchers opt to maintain their unique expertise within their own disciplines and try their best to share their knowledge in order to work on collaborative projects. This makes the results easier to

[6] ‘Publish or perish’ is generally attributed to US educator Logan Wilson, who coined the concept it in his book *The Academic Man: A Study in the Sociology of a Profession*, Ch. 10 (1942). See *The Yale Book of Quotations*, p. 829. However, Clark (2006) notes that this tradition had been encouraged by the policy of Prussia in 1749.

be published and evaluated in separate disciplinary evaluation systems.

Even though IDC promises better research performance than mono-disciplinary-based works, a concrete explanation on how to conduct sound IDC efforts, for instance, how people best suited to share knowledge are identified, the mechanics of who and when to contribute knowledge and what kinds of innovations are appropriate for an IDC project, remains incomplete. With a sound basis in cognitive mechanics of knowledge interaction, this dissertation is able to make practical suggestions for IDC practise to help people understand each other easier and quicker in order to closer approach what IDC has promised.

This brings us to the third and final point regarding the emergence of science research projects as a collective endeavour (Uzzi, et al., 2005; Bendix, et al., 2017). The necessity of revealing interpersonal mechanics of knowledge interaction in IDCs is associated with the new approach to research management that can be hardly responsible by individual scientist but that is project-based and team dependent. Indeed, the team dependent management system has long been evident in disciplinary-bound researches, but it also plays a crucial role in the management of IDC, which usually involves a wide range of researchers from different disciplines and with various levels of seniority. A large-size collaborative research group is typically made up of leading professors, principle investigators (PIs), junior post-doctoral researchers, students of different levels and other technical and personnel assistants, while a small-size IDC group can be as few as two or three researchers. No matter the size of the research group, just as Bendix and her colleagues have claimed, ‘a project is never just a project’ (2017: 5). The whole process of scientific knowledge production means different things to scholars at each level of the academic hierarchy. For instance, professors and PIs might consider the project as a part of a huge network of research topics and potential collaborative projects, doctoral students take it as a paid job and professional training, and postdocs treat it as an opportunity to build their academic reputation, colleague network and a path which hopefully leads to new academic jobs. Apparently, how to divide work tasks, distribute them to various IDC team members, and then integrate them as a joint research project are crucial questions for all scientists who want to contribute to, organise and establish an interdisciplinary team. Thus, this dissertation also examines the management mechanics of IDC teams.

1.5 Knowledge Interaction in Interdisciplinary Collaborations

1.5.1 Knowledge interactions as the core of IDC

The theoretical necessity to study knowledge interactions is associated with the crucial role knowledge interactions play in the IDC practise. IDC, by definition, is a process of co-producing scientific knowledge without fully abandoning one’s discrete, discipline-oriented expertise, methodology and academic community. It implies that people who take part in IDC projects are still able to conduct research in their own respective disciplinary contexts and who also work jointly with people from other disciplines choose to generate integrated ideas by contributing their unique perspectives. In this vein, every single step of scientific knowledge production in the context of IDC and its interpersonal communications when people are establishing a team for interdisciplinary knowledge co-production is somehow related to the exchange, integration or co-production, in a word, the interaction of knowledge.

Certain sets of factors have been found to influence IDC efforts, especially the integration of research concepts from various scientific disciplines, when studying difficulties in making the project possible or successful. Based on factor analysis, Tress and his colleagues (Tress, et al. 2007) divided IDC barriers into three categories: time demands and external barriers, interpersonal and organisational barriers, and academic traditions and epistemological barriers. Also, these barriers are detected when trying to understand the complex building process of IDCs (Whiteside, 2004; Hall, Stevens and Torralba, 2005; MacMynowski, 2007). Based on their insights, below is a classification of barriers that I summarise from prior researches about IDC in the recent decade (Burkart, 2002; Amey and Brown, 2004; Maglaughlin and Sonnenwald, 2005; Klein, 2005; DuRussel and Derry, 2005; O'Donnell and Derry, 2005; Maton, et al., 2006; van Rijnsoever and Hessels, 2011; Hampton and Parker, 2011; Siedlok and Hibbert, 2014; Hamann, et al., 2016; Regina, et al., 2017; Dai and Boos, 2017).

1) *External barriers*, including inadequate funding from the institution, an institution's limited policy support and lack of reward systems;

2) *Interpersonal and personal barriers*, such as different power settings and structure of hierarchical status in each participating disciplinary group, conflicting interpersonal relationships, inappropriate group size, different or long-distance physical locations, various habits of learning new knowledge, communicating with colleagues and evaluating academic 'products' in respective disciplinary communities, irreconcilable personal characteristics, low level of expertise, differences in gender and work language, unwilling to dedicate time, resources and patience, and lack of motivation to participate;

3) *Cognitive barriers*, like limited capacity to understand another's viewpoint in order to deal with misunderstandings, uncommon research goals, lacking knowledge of other disciplines, uncommon terminology and methodology, different research procedures, and so on.

Different from the methodological approach of Tress and his colleagues, which is empirical investigations, my classification of barriers to IDC is given by a literature review. A similar way of classification is derived from the two approaches, except that, at the first glance, some of the barriers considered as cognitive ones, such as mutual understandings and common goals, are also pointed to interpersonal set in previous studies. I claim that they are interpersonal when they are unwillingly to be reached by scientists; if they are unfulfilled because of a lacking of capacity or skills of scientists, they are about cognition. Apparently, cognitive barriers describe the latter situation.

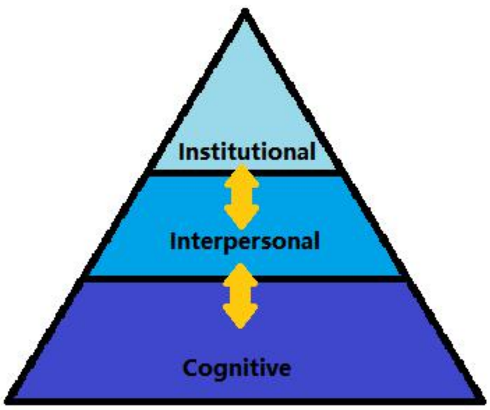

Figure 1.3 A three-level analytic system: on the base there are cognitive activities of the scientists' minds; in the middle, the interpersonal interactions happens in every day scientific research lives; at the top, the Institution – an embodiment of its science community.

These factors may indeed serve as an outline and provide basic perspectives to examine an IDC. In particular, it confirms the legitimacy of a three-level analytic system corresponding to these three barriers (Figure 1.3). At the base of this system are the scientists' cognitive activities; in the middle are their interpersonal interactions occurring in everyday scientific research lives; and at the top is the source of external barriers to an effective IDC – the institution – an embodiment of its science community, which in some institutions has been in place for decades. With the external barriers under control by conducting fieldwork in a single university, this dissertation is able to focus its consideration on the interpersonal and cognitive barriers to an effective IDC.

Focusing on barriers to IDC runs the risk of neglecting the interconnections among different factors. Moreover, these barriers merely suggest what factors might affect an IDC project without answering concretely how exactly they change, sustain or constrain which part of the IDC practise. Nevertheless, to tackle the issue of the cognitive and interpersonal mechanics of knowledge interaction in IDC efforts, it is necessary to tease out a set of more detailed research questions by sequencing the levels.

On the cognitive level:

Sub-question 1 (Chapter Two discussing methodology): what is the proper tool to visualise and analyse cognitive activities?

Sub-question 2 (Chapter Three discussing cognitive mechanics): with this tool, how is knowledge integrated? Delving deeper, what is the minimum degree of knowledge sharing? How is this degree of knowledge sharing established? How is it sustained over a longer period of time and in more hierarchical teams?

On the interpersonal level:

Sub-question 3 (Chapter Four discussing interpersonal mechanics): how do people work interdependently? Specifically, how do people divide their work tasks? What influences their research interdependence?

Sub-question 4 (Chapter Five discussing implements): how is the interpersonal arrangement of an IDC team associated with its performance, namely its efficiency and innovation?

1.5.2 The black box of knowledge interaction in IDC teams

The cognitive processes of knowledge production of scientists remain hidden in the 'black box' metaphor as it applies to knowledge interaction in IDC teams, 'a fiction representing a set of concrete systems into which stimulated impinge and out of which reactions re-emerged' (Bunge, 1963: 346; also alluded to by early researches of sociology of science, like De Gré, 1955; Merton, 1973). Taking the physical and mental energy of researchers, experimental materials and research proposals as input, the scientific community, culture and knowledge in forms of published articles, research reports and technology patents emerge as output (Whitley, 1970), the internal cognitive research activities that transformed the input to output are ignored. In this section, four prior efforts trying to open the metaphorical IDC 'black box' are discussed in order to find a proper perspective to further elaborate and contextualise the research questions mentioned above.

First of all, by focusing on co-publications and inter-citation network (Laudel, 1999; Börner and Boyack, 2010), the internal flow of knowledge across different disciplinary traditions can be traced. The numerous works on bibliographic network analyses indeed illustrate grand trends of researches in specific areas, yet are inadequate at revealing the processes in which knowledge connections are concretely made. After all, the significant distinctions and amount of details between what people are thinking during experiments or investigations and what they write in a report or an article have been identified and discussed by prior works studying how scientific facts come about (Knorr-Cetina, 1981; Latour and Woolgar 1979) as well as the tacit knowledge that forever remains unpublished (Collins 1990; Collins and Kusch 1998). How a research team is organised and pre-collaboration experiences are also playing roles in knowledge transfer and co-production. For instance, Haythornthwaite (2006) asked what kinds of exchanges among scientists established the basis of an IDC. She reported that crucial exchange contents include factual knowledge, methods, technology, the experience of working jointly in the same project, generating new ideas together and accessing a network of contacts. Prior experience of working together in other projects with collaborators is also found helpful in reducing the negative influence of both geographic and disciplinary distance, and increase frequency of communication and emotional closeness, namely the intensity of interpersonal relationships with those collaborators (Cummings and Kiesler, 2008). As well, research teams are easier to be coordinated when project participant come from fewer universities, namely a simpler institutional environment (Cummings and Kiesler, 2005). In this vein, merely investigating the observable parts of knowledge connections, namely the publication and co-authorship networks, is not enough to open the black box.

Secondly, boundary crossing in the field of sciences, as Galison (1997) argued, can be seen as a kind of 'trading zone' that is 'partly symbolic and partly spatial – at which the local coordination between beliefs and action takes place' (1997:781–783). Such an economistic view, however, does tell some elements of truth that collaboration often emphasises exchange and mutual gain. Yet it is often not clear, when it comes to time-consuming communication and collaboration, what the exact 'product' to be exchanged is and how. Bendix and her colleagues (2017), based their first-hand collaborative experiences on an IDC project about cultural property in the German context, argued that the trading zone was not just a short-term commodity exchange, but a gift economy for the longer run in which, just like tourism, 'pleasure or experience is returned for money expended' (2017:17).

In a similar vein, others discuss knowledge integration in IDC from the viewpoint of 'boundary objects'(Star and Griesemer, 1989). It is argued that while the disciplinary boundaries are by and large retained, it is those concepts, technologies and skills that may be interacted, re-understood and converged on these boundaries that constitute an area of cross-disciplinary overlap that makes collaboration possible (Jakobsen, Hels and McLaughlin, 2004; Klein, 2005; Hall, Stevens and Torralba, 2005; Mollinga, 2008; Baggio, Brown and Hellebrandt, 2015). Wesselink (2009) showed that the boundary object, which was the notion of 'landscape quality' in her case study, emerged without explicit intention during the negotiating process among IDC participants. Thus, the theory of complex systems can be deployed to describe the fulfilment of a boundary object in an IDC effort (Newell, 2001). Yet, inadequate attention has been paid to empirically visualising how a boundary object of an IDC emerges in order to determine whether it is at work during the complex knowledge exchange and production processes, how long the boundary object lasts during the processing of an IDC project, or when the boundary object is established and maintained to connect different disciplines in the first place..

Thirdly, a number of tools and protocols have been designed to support the establishment of

IDC (Klein, 1990, 2005; Clark and Brennan, 1991; Selin and Chavez, 1995; Clark, 1996; Jakobsen, et al., 2004; Bergmann, et al., 2005; O'Donnel and Derry, 2005; MacMynowski, 2007; Godemann, 2008). However, if a comparison is made between these protocols and the barriers mentioned in 1.5.1, a logical conclusion emerges: there are likely far more IDC teams than those that these protocols may be able to serve and that the barriers constitute complex situations beyond the considerations of these protocols. They offer detailed steps or sub-goals to those who practice IDC efforts such as 'classification of disciplinary differences' and 'identification of interdisciplinary salient concepts or global question' (Klein, 2005: 43). Indeed, one way or another, people need to achieve these goals. But how in practise can people classify and overcome the barriers to integrating their expertise? In short, the black box cannot be opened by just setting up sub-goals of those kinds.

Another model of explaining mechanics of knowledge interaction in IDCs, as the forth effort, is the 'Mode 2' claimed by Gibbons and his colleagues (1994). They proposed that the patterns of knowledge production have shifted from the discipline-based 'Mode 1' to the trans-disciplinary 'Mode 2'. Mode 1 is defined as a process of knowledge production in which scientific questions are generated from the inner logic of a discipline (Gibbons et al., 1994), sets of taken-for-granted values of research behaviour are formed (Becher and Trowler, 1989) and academic researchers are grouped into small communities. However, in contrast to Mode 1, in Mode 2, knowledge is not developed by a group of researchers within a single discipline. Rather, it is distributed and carried as expertise of individual scientists and is manufactured in the process when researchers from various disciplines, who are embedded in an academic network, have gathered together to form temporary research groups. As a result, disciplinary boundaries become blurred. Also, in Mode 2, scientific knowledge is distributed as expertise of individual scientists. In the process of producing and reproducing trans-disciplinary collaboration, scientists combine and integrate distributed knowledge together, organising themselves in a certain way in order to solve practical problems. With the research target fulfilled, new knowledge is produced by participating scientists who may or may not have had prior collaborative experience with each other, and deploy accumulated expertise to solve new problems.

The shift from Mode 1 to Mode 2 does not mean a complete disappearance of Mode 1, nor does it show that Mode 1 has become less important (Gibbons, et al., 1994). As Nowotony and her colleagues (2003) stated, Mode 2 emphasises the changing academic environment in which knowledge is funded, produced and applied in ways different from those of conventional research. In particular, it describes five characteristics of the new mode of knowledge production in today's realm of academia: (1) generated within a context of application, (2) is trans-disciplinary; (3) involves a greater diversity of knowledge production sites and of types of knowledge; (4) has high reflexivity; and (5) uses novel forms of quality control (2003:186–188).

The analytical models of Mode 1 and Mode 2 have faced enormous criticism since the publication of *The New Knowledge Production* in 1994; as a result, there have been multiple rounds of debates and revision of the arguments from the authors (Nowotony, et al., 2003). Often criticised for being relativist and over-simplified, Mode 2, I hold, provides an important new and pioneering perspective at that time to point out new changes of knowledge production on the macro level. It implies that the dependence of researchers to produce new knowledge has come to rely on temporary, cross-discipline teams rather than within single disciplines. However, lacking empirical studies, Mode 2 remains a floating hypothesis rather than a theoretical framework with solid empirical evidences. It is, in the words of the authors, 'an example of the social distribution of knowledge' (2003: 180), formulated in order to call for more researches to capture new modes of knowledge production culture. Even though not all IDC teams are temporally established, nor are they without a hierarchy as Mode 2 has assumed (most of them are bounded by research projects), the point the authors are making is that there has been an organisational paradigm shift to overcome discipline boundaries in order to create new scientific knowledge. Partly as a response to this call, this dissertation moves the dialogue of Mode 2 forward by embarking an empirical study on the micro dynamics of knowledge production.

1.5.3 Opening the black box

In order to open the black box of knowledge interaction, it is crucial to examine what is happening in people's minds when they are conducting daily scientific works. In contrast to the contrived protocols, abstract task boundaries and late results that characterise IDC projects, this dissertation calls for practical, concrete, individual and structural understandings (further elaborated in Chapter Two) of the scientists working on actual IDC projects. In other words, the key to opening the black box of IDC knowledge exchange and production is an examination on the scientists' cognitive approaches to different scientific work. By mentioning the cognition of a scientist, I do not mean how neuron networks in his/her brain work. What I set forth are understandings as a set of concepts, methods, people, research targets and any other objects affecting the scientists' approach to their research. Until we understand what a scientist is thinking regarding his/her work at the very present practical, concrete, individual and structural cognition levels can we understand how these thoughts, as knowledge, are exchanged, integrated and co-produced. I will show in this dissertation how the process of knowledge interaction is associated with ways people organising their IDC teams; who does what in what stage will be clearly shown by comparing their individual cognition on scientific works. Further features of the cognitive structures of knowledge will be discussed in Chapter Two.

It is worth noting that this perception of knowledge as personal understandings is the basis of the relativistic and constructive view of scientific knowledge. In this version of knowledge, the Sociology of Scientific Knowledge (SSK) considered scientific knowledge as the 'expertise and experience' of scientists (Collins and Evans, 2002: 238; Latour and Woolgar, 1979). For instance, Collins argued that 'no knowledge of what lies hidden beyond human scientific activity is claimed' (Collins, 1983: 267). Rather, negotiations were always found between scientists because they might have different interests in certain aspects of the same experiment, which resulted in different understandings of the same result (Collins, 1975). Knowledge appearing as a kind of controversy has also been discussed in Pinch's work (1977), in which he presented how a faulty mathematical proof was used to inspire the development of quantum physics. In parallel, just like what Collins argued, in the field of IDC studies, Burkart (2002) reported that, in the inter/trans-disciplinary team, what a speaker meant sometimes could be quite different from what the listener understood. In the same vein, the IDC case study conducted by Jakobsen, Hels and McLaughlin (2004) reveals that the difficulty of cross-discipline understandings is caused by different meanings of the same vocabulary and the unawareness that these differences exist – scientists of different disciplines may reach an agreement even when they do not completely understand what others have said.

Compared to Collins and Pinch, the laboratory studies observe a much more detailed and dynamic process of knowledge production. Latour and Woolgar (1979) pioneered a new field of studies and examined the social life of scientific research in a biochemistry laboratory. They took an anthropological approach that allowed researchers to observe day-to-day actual scientific work process in laboratories, and held that this approach had the potential to reveal the ways in which knowledge was manufactured. Consequently, scientists are found being socially embedded in specific research positions regarding the roles they play in the process of knowledge production, such as junior technicians, senior technicians, scientific researchers and others. These positions form a social hierarchy in the laboratory. In this hierarchy, people in higher positions manage more expertise, so they are harder to be replaced than those in lower positions. In this way, people divide their work by the positions they hold in scientific research teams. In parallel, scientific knowledge is found constructed in a highly internal structure, which is externalised into scientific documents such as experimental reports and calculation drafts (Latour and Woolgar, 1979), or various orders of selected tools, equipment and materials (Knorr-Cetina, 1981). These selections are made by 'particular agents at a particular time and place…by particular interests of these agents…by local rather than universally valid interpretations' (Knorr-Cetina, 1981: 58), namely, by the said agents' cognitive activity that produces and tests scientific knowledge.

Such a relativist and constructive view on knowledge and knowledge production is proposed against an older perspective in the history of scientific knowledge studies, which is the objectivist view on knowledge. An objectivist understanding of knowledge is that the world is operated by the guidance of 'natural law' that is universal and permanent, and scientific knowledge is the product of people's attempt to grasp this law. Therefore, scientific knowledge is objective and independent from human beings; knowledge is all about the truth of the world. For example, Mannheim (1936) made a clear distinction between the knowledge of natural science and historical thought. The former is dedicated to discover the truth of the natural world that is considered independent from human interpretation, while the latter is in general the interpretation of human and cultural phenomena, which is significantly depending on social circumstance in which values and meanings are understood differently and dynamically (Mannheim, 1936; 1952). Accordingly, knowledge production is considered as a process in which scientists try their best to avoid mistakes and bias in order to find 'true' scientific knowledge. Knowledge produced in the sphere of social sciences, like that in the natural sciences, is the objective 'social fact' (Durkheim, 1938), independent from individual influence, even though its content might be different from one social community to another. In this sense, knowledge produced by social scientists should be considered as true scientific knowledge. Per the objectivist perspective, it is believed that it is not necessary for sociologists to examine the context of scientific knowledge itself (De Gré, 1955).

1.6 Researching Interdisciplinary Collaborative Research Teams

1.6.1 Introduction to the fieldwork of IDC teams

This dissertation examines interdisciplinary research projects in a modern German context. From the year 2012 to 2016, I worked intensively with a number of scientists who collaborated with each other at a German University. I chose this university because it is a traditional and representative one. Like most highly rated German universities, it is a comprehensive university with thirteen faculties, more than one hundred and seventy research centres and institutes and five Max-Plank-Institutes. In addition, it has a relatively long tradition of interdisciplinary collaboration that continues to be strongly supported by the university's administration.

My fieldwork research time can be divided into two parts (see Table 1.1). The first part is the pilot study, which started autumn of 2012 and finished February of 2014. The second is the main part of the fieldwork, which lasted two years and finished end of 2016.

At the first stage, I observed an interdisciplinary collaborative group I will name 'CSP' (computer scientists, social psychologist and physicists). Group members came from five different disciplines: computer science, sociology, psychology, physics and medical science. They held several meetings and established their interpersonal relationships from 2010 to 2012. Then in order to overcome difficulties of knowledge integration, they began an interdisciplinary seminar in the autumn semester of 2012, which was when I initiated this fieldwork. After another half year of detailed discussions on concepts and theories of each discipline, and with new members entering and leaving the group, two additional, smaller project teams emerged.

Table 1.1 An outline of the fieldwork data

Stage of Study	Pilot Study (2012—2014)	Fieldwork Study (2015—2016)
Number of project teams and informants	three project teams (15 informants)	four project teams (19+3 informants)
Disciplines	computer science, sociology, psychology, physics	physics, statistics, biology
Number of cognitive maps	24	40
Number of interview records	37	65
Number of participating observation	24	2
Places	semina room, office	laboratory, seminar room, office
Participants	only senior researchers	both seniors and juniors

I was able to take part in twenty-four of their twenty-seven IDC meetings in these two and half years. In addition to attending their meetings, I interviewed fifteen of the twenty-eight participants (senior researchers such as full-time university professors and post-doctoral researchers; junior researchers such as master and doctoral students). Some reasons for the inflexibility of many I requested to interview may have been due to the inherent difficulty of 'study up' (see 1.6.2). Another possibility could be my informants' unwillingness of rearranging their full schedules, and/or of speaking English, as interviews could only be conducted in English. Interviews were conducted at least twice with all but two participating informants (they had left the project by the end of 2012) to check whether there had been a change of understanding on the joint project. These interviews are substantiated by thirty seven records of interview, sixteen records from participant observations and twenty four cognitive maps (see Table 1.1). Finally, even though both senior and junior researchers were investigated, only the data garnered from senior researchers were used in this dissertation. Analyses of the cognitive mechanics of knowledge interaction in Chapter Three are mainly based on this set of data.

At the second stage (2014–2016), I was involved in an extensive research network consisting of hundreds of physicists, biologists, chemists and statisticians of the same university. This network was linked by the Deutsche Forschungsgemeinschaft (DFG; English: German Research Foundation), a German research funding organisation and one of the largest research funding bodies in Europe. Even though these scientists were not working in the same DFG unit, they were keen on initiating collaborations. I formed fieldwork informant contacts with five research groups and nineteen key informants. Two physicist groups were led separately by John and Bob; two statistician groups were led separately by Will and Ling; and one biologist group was led by Chris (all names are anonymised). Together they comprised four project teams, which I will refer to as the 'BPS' (biology, physics, and statistics) group. Three additional informants, Jack, Shylock and Jenny, who came from two other physics groups, provided information of great value at the beginning of this fieldwork. At each of the three stages, I conducted interviews with all members of the IDC team, including professors or PIs, post-docs, doctoral, master and bachelor students and HiWi (wissenschaftliche Hilfskräfte; Eng: research assistants). Taken together, both senior and junior researchers were investigated. More details about each interdisciplinary research collaborative group will be discussed in Chapters Four to Five. The reason for interviewing all group members will be introduced in section 1.6.2 and expanded upon in Chapter Four.

1.6.2 A fieldwork of 'study up'

The fact that my fieldwork lasted over so many months, to a certain extent, reflected the difficult nature of 'study-up' research in general (Jasanoff, 2010). Like many other science and technology studies, most of my informants were full-time professors and PIs who enjoy high socio-cultural status and have extremely packed work schedules. At the beginning of the fieldwork, I encountered numerous setbacks. After sending out countless introductory emails to the heads of various selected research institutions, I received far more silence than a few quite rude replies. One exception is a written refusal from a kind theologist, whose email started with the following sentences: 'young colleague, I am sure there are other projects that meet your need. But I am quite busy…' Indeed, the fact that I was a 'young' colleague-trained social scientist whose fieldwork was dependent upon other scientists being willing to donate their time prevented me from being able to have an equal dialogue with many senior researchers. Another factor that likely prevented senior scientists from being willing to be interviewed is that I was seeking interviews with scientists in a German University but was linguistically limited to conducting these interviews in English. This unbalanced power- and linguistic-relation remained throughout my fieldwork. It made me reflect on the results of my pilot study, which were primarily based on investigations of the project leaders: students had perhaps also made remarkable contributions to IDC building but their contributions went either unnoticed or unacknowledged by both the interviewed project leaders, or also by me. I include these somewhat anecdotal fieldwork experiences because they are likely indicative of the real-world barriers an IDC researcher can face. My inclination to omit data from informants in lower positions of the hierarchy can also be judged as anecdotal, but indeed implies a potential tacit tension between how the quality of data provided by researchers in charge of the project is perceived relative to how the data of those who are less experienced in working in a large, professional project are perceived. That is why in Chapter Four and Five, there is an explicit examination of the cognitive maps of all group members. In addition, I also conducted fieldwork observations of two young researchers participating in an IDC, conversing with them while they worked in their laboratories for an entire day. Insights garnered from Leo the biologist and his fellow collaborator, Albert, from the department of statistics (not their real names), appear in section 1.1 and Chapter Four.

Apart from the apparent power dynamics present in academia, another difficulty lies in the fast pace and demanding nature of academic professions in general. In order to survive and thrive in a highly competitive research field, my informants needed to calculate how they could get the most from their limited time. Thus, to help an unknown young doctoral researcher who requested access to their daily research life and first-hand experience, data, and research ideas apparently seemed too time-consuming and risky. Even though most professors and PIs in my fieldwork were very kind and professional, I still conclude this calculative logic from their words and attitudes, as highlighted by the anecdotes above. Just like Jack had told me, 'you have to play according to the rule of academic capitalism. But it is your decision to just follow the trend to create some rubbish for your career promotion or to do the real science.' Thus, my fieldwork experience also reveals and speaks to some of the key arguments running throughout this dissertation on opening the black box of real-life cognitive interactions in IDC and the barriers potential cognitive exchanges face, especially how potential interactions can be affected by the ways in which modern scientific researchers manage their time, labour, and intellectual currency. Findings related to this topic will be shown in Chapters Three and Five.

The nature of their professional positions also appeared to make them more critical sometimes – even sceptical, bordering on suspicious – about the scientific research I conducted. An extreme example I experienced during the fieldwork was when a geology professor waved a yellow covered research report in his hand and directly asked me, 'are you a spy from Chinese government? You know, if you sell this report to your government, you will earn a lot of money!' As well, in the beginning of the pilot study, a computer scientist told me when I arrived for our appointment that 'I will not take part in your research because your project is meaningless to me'. From these refusals, I gradually realised that big bosses were so busy that I should make my interviews as concise and packed as possible. So I usually limited the duration of my interviews to within one hour. To a certain extent, the relative junior position that I was perceived to be in during many of these informant–researcher relations allowed me to play the 'innocent card'. As a 'junior researcher', I was allowed to ask basic, sometimes even naive questions about the basic knowledge of the discipline, which may not have been possible if I was seen as a senior, experienced researcher with superior status. Furthermore, I suspect my informants would rather accept an innocent sociologist than a 'young colleague' trained in the same discipline, as this meant I posed no competitive professional threat. My research network started to expand after I received the initial acceptance of a few good-hearted professors, who not only supported my research, but also introduced their colleagues and students to me. This snowball phenomenon proved to be a very slow yet effective method for obtaining access to members of the highly protective and vigorously challenging scientific communities.

1.7 An Outline of Chapters

The intent of this first chapter is to build the basic analytic framework of this dissertation. It introduces the research questions of this dissertation. By reviewing the basic definitions of IDC and knowledge interaction, my research target has been clarified. Practical and theoretical necessities of this research are discussed by summarising the backgrounds of IDCs and the multiple ways of opening the black box of knowledge interaction. Finally, an outline of my fieldwork and data structures have been illustrated. Sub-questions have also been set up and will be teased out in the following chapters.

The next chapter (Chapter Two) introduces the methodology and highlights a technology of visualising the structure of scientific knowledge: cognitive mapping. With the help of participant observation, semi-structural interviews and the cognitive mapping approach, the interactive process between the sharing of knowledge and the division of academic labour is examined. In particular, based on previous research (Dai and Boos, 2017), Chapter Three discusses the cognitive mechanics of knowledge interaction in IDC teams established by only professors and PIs (from the aforementioned 'CSP' group). It teases out contextualisation and integration processes from which boundary objects for a specific interdisciplinary research topic are derived by ethnographic accounts and cognitive maps. Moreover, how boundary objects last in term of time/stages of IDC research and a larger and more complex IDC group of people (with also junior researchers) are examined. In Chapter Four, interpersonal mechanics are discussed by showing who does what in what stage, namely a division of scientific labour and working interdependence, followed by a conceptual dialogue with prior studies focusing on intellectual structures and related organisational structures. In Chapter Five, how an IDC team can be run efficiently and who contributes to which part of an innovation are examined as applications of cognitive and interpersonal mechanics of knowledge interaction. Finally, in Chapter Six, findings will be summarised. Extended discussions covered in this dissertation and conclusions with some final remarks are given, including policy advice on organising an IDC project as well as additional insights into this dissertation' introduction of the embeddedness relationship between cognitive structures and interpersonal structures of interdisciplinary scientific teams.

Chapter Two

Visualising Knowledge Interaction

In order to understand the mechanics of knowledge interaction, it is of prime concern to clarify what is meant by ‘practical, concrete, individual and structural understandings of the scientists working on actual interdisciplinary collaboration (IDC) projects’ mentioned in the section 1.5.3. This chapter will introduce the methodology designed and employed in this study of interdisciplinary collaboration, namely the method of semi-structured interviews, participant observations and, of most significance, cognitive mapping.

2.1 Understandings of Scientific Works

2.1.1 Research target

Three totally distinctive claims on the concept named ‘social network’ by a computer scientist, a sociologist and a physicist (all in the ‘CSP’ group) vividly illustrate the phenomenon conceptualised as ‘understandings of the scientists’ and the complexity of reaching a shared cognitive base for working on a scientific project.

After two years of regular meetings, the ‘CSP’ group members realised that the differences of understandings of the concept ‘social networks’ was one of the most fatal problems blocking them from fixing concrete collaborative research topics. In the interview, the sociologist defined that a social network was a method that was able to visualise and analyse the structure of interpersonal relationships of both online and offline. The social network meant also a set of sociological theories consisting of concepts such as strong ties, weak ties, and structural holes, by which one could study a group of people both quantitatively and qualitatively. The physicist conceptualised the network mathematically as a graph. He said if one calculated for example the degree distribution of a network, especially the citation networks among scientists or friendship networks on Facebook, he/she would get a power law, which was potentially a natural law that excited physicists. It was believed so because the power law could be found also in the World Wide Webs and other networked communities, namely was probably universal. Computer scientists took a more practical approach. One told me that a social network was Facebook, Twitter, or any other online applications of this kind.

The production of scientific knowledge consists of a series of complicated sub-tasks, choices and decisions (Yearley, 1990). For instance, a scientist has to decide what to study and which academic field he/she engages in. This kind of decision-making can be reflected through the process of conceptualisation. In this process, a scientist chooses perspectives to study the nature of a particular natural or social phenomenon by a series of research steps. These research steps usually follow the relatively standardised sequences of conducting academic researches (Turabian, 2007; Babble, 2010), including defining and operationalising concepts, setting up parameters and controlling conditions, proposing research questions and so on. Prior knowledge from textbooks and existing scholarly literature provides the platform, in dialogue with which a scientist may generate new scientific knowledge.

In this vein, in the case of 'CSP' group, the three above-mentioned members generate distinctive processes of conceptualisation of the concept of 'social network'. Among the three of them, the sociologist is the only one who claimed that the concept of social network was already the results of a conceptualisation, namely 'a set of theory' and 'method' that emphasised and abstracted structural properties of interpersonal relationships. This may be due to her research interests as a sociologist focusing on social structure, social capital and labour market related theories. Compared to her, the physicist took social networks as a research target or a social phenomenon to be studied. In other words, the concept and model that the sociologist deploys to study her research targets are the research targets of the physicist. Having learned from prior researches and his own pilot studies, the physicist decided to deploy the parameter of degree distribution, which represented the degree of popularity of nodes in a network. The unspoken epistemology behind was that he in the first place removed the social attributes of a network by considering a so-called social network merely as a mathematical graph. For the computer scientist, by contrast, the social network meant merely online platforms that people were able to communicate with each other. Thus it was also the research target, that is, a kind of phenomenon under study, for him.

Also, as a scientific researcher, one is trained to become experienced in how to undertake an academic research by mastering a set of protocols, skills and methods. The case of 'CSP' group, for example, shows a diversity in research expertise and methods deployed by different researchers: the sociologist in the 'CSP' group is good at conducting qualitative and quantitative research methods such as interviews and questionnaires; the physicist is good at setting up physical models by mathematical deductions after statistical analyses of the data has been carried out; the computer scientist builds up simulation models, codes program and calculates several network parameters

Furthermore, a scientist is supposed to establish and test hypotheses and to establish innovative theories. The sociologist aims at examining social phenomena and developing sociological theories; the physicist tries to find universal laws at work in all kinds of networks; the computer scientist intends to develop an online application with algorithms providing personalised advertisements and recommendations

Plus, in an IDCT, one also needs to decide from which team member he/she asks for expertise supports and to which he/she offers the service. It is significant for scientists to carefully choose collaborators and to negotiate with them if required. Decisions must be made when IDC team members are keen on facing problems together during the process of the joint research or when it comes to an end of their collaboration by breaking up with each other and abandoning the project team.

It is a common sense that scientist's considerations on academic and practical knowledge and research resources, such as the phenomena under study, concepts, methods, equipment, skills, hypotheses, theories and research goals, and on ways of organising them, are all running in one's minds. Thus understandings and actions of scientific research can be draw out from the minds, if the minds are to be visualised. How scientific knowledge is constructed and operationalised is not an one-off business; rather, this process, which can be full of turns and twists, can be extremely unclear and is deeply hidden in the ordinary, mundane scientific labour works. This dissertation, therefor, intends to shed light on the micro-sociological, interactional and cognitive operation of how scientific knowledge is produced, debated and understood in an inter-disciplinary collaborative setting.

But what seems extremely difficult is to critically examine the process of these understandings, which certainly change over the progress of the IDC project. To better visualise and analyse those cognitive dynamics, we are in need of a tool, which may have the following four properties.

1.1.2 Four properties of a potential tool

First, since the understandings running in every individual scientist's mind are personalised, the form of data should be able to represent individual scientist's cognition on the whole project he/she is working on, rather than the general epistemic structure of the entire research field (Whitley, 1974) nor constructed knowledge shared by a social group (Pinch and Bijker, 1984) in a larger scale. It should enable spaces of self-reflection on the contents, objects and strategies of one's own research as well as understandings on the collaborators' works. In this vein, it should be able to highlight distinctions of knowledge between individuals' minds while at the same time to potentially illustrate how knowledge is inter-connected.

Secondly, these understandings may change along with the progress of the project during the time that a new experiment is designed and undertaken, a new set of data is collected, and a new hypothesis is claimed and tested. Through everyone's mind, these knowledge processing progresses draw epistemic trails of the joint research project. So the means should illustrate both the history and the moment of what a scientist is considering in the project. In other words, both dynamic data and cross-section data should the tool provides and analyses.

Thirdly, in the context of IDC, to illustrate the interaction processes between various knowledge systems is of great importance. These connections of knowledge include the exchange, sharing and integration of personal understandings of the knowledge at work in the project; knowledge systems change according to each other. In this vein, they serve as 'horizontal' communications of the scientist's understandings of the project, if the second property can be considered as 'vertical' dynamics of one's own ideas. Their effects on each participant during the progress of the project should also be shown by the tool.

Fourthly, the tool should illustrate not only the content of knowledge at work in minds, but also how one organises his/her work in the project with resources and ideas. Thus inner structures of knowledge presenting how each component of the understandings is connected with each other should also be illustrated by the tool. Surprisingly, even though the intellectual structures, protocols, task boundaries and citation networks are lacking of at least one of the properties listed above, it might not be a coincidence that they can all be presented in a form of network. What may be reasonable is that they all try to consider a kind of structure of knowledge.

2.2 Interviews and participant observations

In this dissertation, I deploy the methods of participant observation, semi-structural interviews, and within which, cognitive mapping. They serve as tools to collect distinctive types of data.

The participant observation provides vivid experiences on the practical research activities of scientists in IDC teams. Taking part in group seminars and daily lives of scientists, I am able to observe real-time practice of scientific works, debates and communications within the team. Thus

I learn how a PI set up a research question, how a Ph.D student conduct experiments and analysis data, and how people, with various goals, deal with misunderstandings. Number and basic situations of informants have been listed in the Table 1.1 and, especially for the information of the 'BPS' group, Table 4.1. Scenarios for participant observations have been briefly introduced in the section 1.6.1, and will be further elaborated in details in the section 3.2 for the 'CSP' group and the section 4.1.4 for the 'BPS' group.

The goal of conducting semi-structural interviews is to tease out not only thoughts the informants are considering during the work process but also the strategy one uses to conduct the research work, the history of a particular research project and the reason one picks up his/her collaborator. Number of interviews can be found in the section 1.6.1 and 4.1.4.

Participant observations and semi-structural interviews are two main methods deployed to investigate knowledge interaction by prior studies. However, it is quite hard to reveal accurate knowledge structures from interview reports and ethnographic accounts. Thus packed in semi-structural interviews, I deploy the method of cognitive mapping, which will be carefully introduced in 2.3.

It is worth noticing that the cognitive mapping and interviews can not replace each other, for they respectively provide unique kind of information: maps are able to reveal contact and structural properties that can never be found by interviews; though maps are collected during interviews, the followed up information collected by interviews can not only support what shows on the maps, but also further explain why patterns and modes from maps emerge as they are.

2.3 The method of cognitive mapping

2.3.1 Cognitive mapping

This dissertation deploys the cognitive mapping (Axelrod, 1976; Boos et al., 1990; Boos, 1996; Budhwar, 1996; Ohm and Madsen, 2004; Dai and Boos, 2017, 2019), a method that analyses human cognition by graph theory, to visulise the understandings of scientists. A cognitive map is made up by nodes and links. In this study, nodes represent single scientific notions,[7] such as concepts, methods, names of colleagues, equipment, relevant events, or data. Directed links between the nodes are employed to show logic relationships between those scientific notions. These relationships include belonging, examples, deduction and comparison. In this vein, a cognitive map consisting nodes and links illustrates an individual's knowledge system (Dai and Boos, 2017).

Not only the content of knowledge, but also social attributes of every single scientific notion are made visible in cognitive maps. It is accomplished by illustrating nodes in various colors and shapes. In this dissertation, in particular, yellow color represents biology/psychology terms, red for physics and blue for statistics/computer science. Sharing parts between disciplines are illustrated by mixed colors. Triangles represent works of junior researchers only, circles from senior only, and squares from both.

In addition, as a network, a cognitive map can not only be presented *in a graphic form*, but

[7] In Dai and Boos's (2017: 43) article, nodes are defined as single scientific terms. In this dissertation, I consider cognitive maps in a wider range, namely nodes are not necessarily scientific terms but all kinds of notions in minds. After all, terms need to be exactly defined and accepted in the context of a certain scientific field, but a notion can be just an idea.

also be represented as *a numeric matrix*. Thus similar to other approaches based on graph theory, for instance social network analysis (Freeman, 2004), a set of parameters can be employed to describe structural properties of a cognitive map in a mathematical way. Specific parameters that were used in this study like sharing of nodes and density of the network will be introduced and further described in Chapter Four and Chapter Five.

The dynamics of people's minds can be illustrated by a set of cognitive maps collected over time or stages in the collaborative process, just like videos are made up of sequences of pictures. In this way, a cognitive map on the one hand represents the current knowledge structure in a scientist's mind and on the other hand analyses complex interactions of knowledge in a structural and dynamic way. As well, a comparison between maps of two scientists at the same stage vividly shows in details how a boundary object (Star and Griesemer, 1989) looks like. In particular, Dai and Boos (2017, 2019) have defined two kinds of knowledge sharing: if the couple of maps contain nodes with the same name and meaning, these overlapping components of the maps are considered as shared knowledge; a sharing of a certain knowledge structure is figured out if not only the name of nodes but also directions of links that are connecting these nodes are shared.

2.3.2 Drawing cognitive maps

In order to avoid systematic errors like linguistic misunderstandings and unintentional adding or omitting interviewer's ideas into the map, informants are instructed to draw their own cognitive maps during semi-structural interviews. In the first-round, informants are encouraged to draw the maps according to the interpretation of the current state of the IDC project. As different informants occupying different niches of the IDC project, they are found to be more interested in drawing scientific notions that they believe to be related to the project and that they intend to show in the time of interview, rather than providing an 'objective map' consisting of all notions about the project. In other words, there are always notions that they think not related to the current stage of the project (even in general these notions are related to the project) or that they won't show on the map in order to prevent their core critical scientific ideas being read by competitors before being published by them. Compared with the other methods listed in 1.5.3, data collected through cognitive mapping at different stages of their IDC projects captures the real-time yet changing understandings on researcher's positions, roles, and the IDC project in general.

A cognitive map is not a Durkheimian 'social fact' (Durkheim, 1895). It is individualised subjective and always changing, and can be merely partially shared by a certain group of people, if at all. In this Chapter, it is argued that cognitive maps that are structured as networks can be interpreted as 'projected' (Heidegger and Grene, 1977) from the subjective scientific knowledge in people's mind, which is the object this research tries to study; by drawing scientists' conceptualisation of their research targets, the cognition of the researcher, that is, in this dissertation, mine, has been adhered to the sphere of the research target, namely informants' cognition. In other words, informants' understandings on their research project and the cognitive maps they draw are isomorphic. Yet slightly different from a Heideggerian projection, in the process of cognitive map drawing, the projection is operated as a result of joint efforts between informants and the interviewer.

A general principle of data collection is that cognitive maps of the whole group were collected at roughly the same point in time so that they could be compared at the similar stage of the collaborative project. Usually, each participant of an interdisciplinary research group was asked to draw his/her cognitive map by the same instruction and in the same week; every one to two months, one-hour semi-structural interviews were conducted on all team members of an IDC team. Three rounds of such kind of interviews revealed the cognitive and organisational developments of these teams. Thus for each team, the whole process of such kind of following up data collection lasted around six months. In each point of time, the informant was also asked to give a detailed explanation of the map he/she draws; when not clear, the informant was invited to answer a series of semi-structured questions.

Table 2.1 The procedure of conducting a cognitive map

Step	Actions
Step 1(by interviewee)	To list a wide range of scientific notions (scientific terms and detailed practices)
Step 2(by interviewee)	To provide necessary interpretation of these notions
Step 3 (by interviewee)	To display those notions and draw links among notions
Step 4 (by interviewee)	To mark social attributes (e.g. the disciplinary categorisation of certain notions, the division of labour illustrated in the map)
Step 5 (by interviewer)	To digitalise the cognitive map in the form of a graphic network

As shown in table 2.1, a typical instruction goes as follows: 1) at first, the informant is asked to list each one of scientific notion[8] on each single card. One can list as many as he/she wants. 2) The informant is asked to interpret the meanings of listed scientific notions in order to ensure that the interviewer understands them well. A common way to achieve this goal is to explain these notions in details with an extremely plain language, which is normally used when introducing scientific works to the public. If some similar notions have been mentioned in other informants' maps, the interviewer must be able to understand what are the similarity and differences between meanings of these notions so that an analytical comparison between them can be undertaken. In the case of two informants using the same name with distinctive meanings of the notion, each of them will be asked to write down more details to further differentiate the notion from the other. In principle, two maps shared overlapping notions when those notions observably carry similar meanings and are described in equivalent vocabulary. 3) The informant is asked to display cards on a sheet of paper and to draw links and write meanings of those links between these cards. As introduced above, these links illustrate various relationships among scientific notions. 4) Social attributes like which participants work on which notions and which notions belong to which disciplines are marked by informants. 5) The graphic map is transcribed into a digitalised graph of network form by the software of UCInet. Figure 2.1 gives an example of cognitive map drawn by a biologist informant and Figure 2.2 shows the digitised form of the map in Figure 2.1.

[8] In Dai and Boos's (2017: 43) article, nodes are defined as single scientific terms. In this dissertation, I consider cognitive maps in a wider range, namely nodes are not necessarily scientific terms but all kinds of notions in minds. After all, terms need to be exactly defined and accepted in the context of a certain scientific field, but a notion can be just an idea.

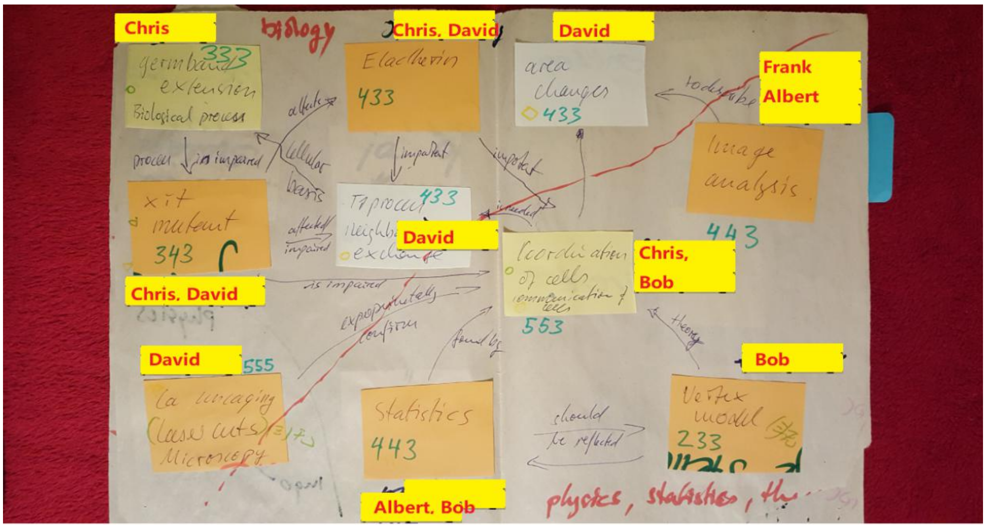

Figure 2.1 An example of a cognitive map conducted by an informant during the interview. Names mentioned on this map have been pseudonymised in order to protect the privacy of informants.

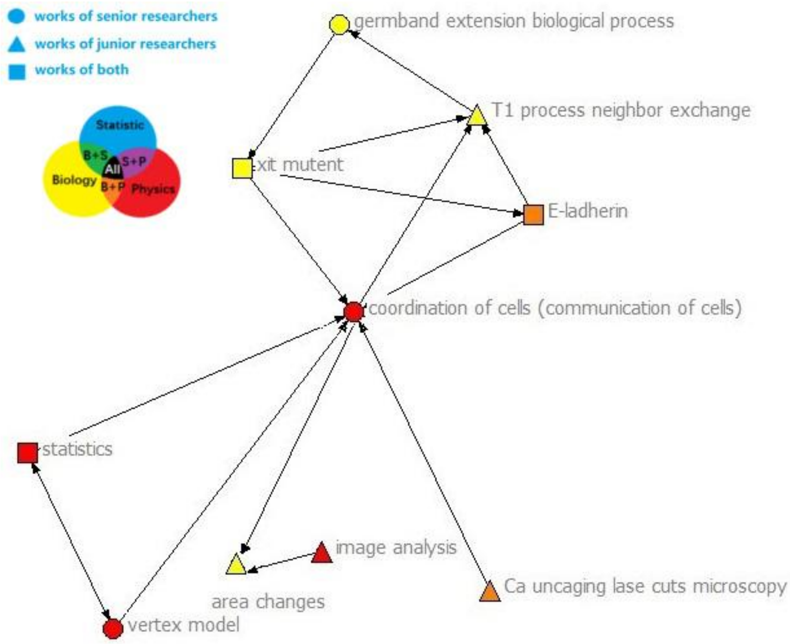

Figure 2.2 An example of a cognitive map digitalised by the software of UCINet (https://sites.google.com/site/ucinetsoftware/home). This map is colored in order to symbolise different scientific disciplines: red color represents notions in physics, yellow in biology and orange in both physics and biology. The circle shapes are works conducted by merely senior researchers, triangles by only juniors, and square by both.

2.3.3 Comparing with other forms of map

The method of cognitive mapping is designed by deploying various methodological and epistemological insights from four mainstream network-formed methods: social network analysis (SNA), actor network theory (ANT), mind map and knowledge graph. The network form implies that all five methods deal with dispersed objects and relationships between them. Although some of them may claim themselves as theories, whilst indeed plenty of background theories are sustaining the certain method and rich and influential mid-range theories[9] are derived from them, here we consider merely from the perspective of analytical technology and the methodology behind. Many other similar network-formed methods such as concept mapping also exist, yet provide no more essential insight on methodology beyond the four ones discussed in this paragraph.

Social network

The well-known social network analysis (SNA) is a set of graph-theory based technology that investigates the structural relationships between people and between organisations, such as firms and academic departments (Wassermann and Faust, 1994). An essential distinction between a social network and a cognitive map, clearly indicated in their names, lies in the differences of the target group, namely what the nodes and links/ties/lines represent – organisations or persons in social networks, versus notions in cognitive maps. Apart from that, cognitive mapping shares the same mathematical approach, namely matrix algebra and graph theory, with SNA. Thus parameters deployed to analyse structures of a social network are also valid to a cognitive map. In this vein, the latter can be seen as a 'social' network of scientific notions. In addition, it is possible that cognitive maps reveal one of the mechanics of building or cutting social network ties (Dai and Boos, 2017). From the perspective of multiple networks (Lazega and Snijders, 2015), cognitive maps of an individual person may serve as the 'capillaries' of his/her social network, meaning the latter can be considered as a (interpersonal relationship) network of (notion) networks.

Actor network theory

Actor network theory (ANT) is an analytical framework depicting the network of heterogeneous entities, including both humans and non-humans (Latour, 1987). The key idea of ANT is to emphasise the agency of both persons and objects when the latter have successfully found an agent to establish or cut relational ties. In an actor network, both persons and objects interact with other agents as human agents do. They are equal under the perspective of inter-subjectivity. Based on this idea, in a cognitive map they are also treated equally because they are all understandings of an ANT-sense human actor. In other words, in a cognitive map they are all subjective reflections of a scientists minds, thus have no agencies.

Mind map

The mind mapping approach is developed and published by Tony Buzan (1974), who with his colleagues further established the software iMindMap. The mind map is mostly used as notes of learning, memorising and integrating knowledge, and of setting up and organising plans. Like a mind map, the cognitive map also represents how the drawer(s) construct his/her own knowledge system in their minds. What differentiates the cognitive mapping approach from mind mapping is that the former sheds lights on both content and structure of the knowledge system, thus structural parameters in graph theory can be employed to find out patterns of knowledge sharing. It is fair to

[9] For instance, SNA contains several grand theories as theoretical bases, like embeddedness (Granovetter, 1985), as well as quite rich and influential mid-range theories such as structure holes (Burt, 1992), vacancy chains (White, 1970), small world networks (Watts and Strogatz, 1998) and so on.

claim that the mind map can also be analysed by the same mathematical tools. But prior researchers rarely conduct such kind of analyses on mind maps because this method was originally designed to emphasise only the content by creatively painting all kinds of shapes, colors and forms of nodes and lines in order to help people better arrange their minds.

Knowledge graph

The knowledge graph is launched by Amit Singhal (2012) who developed online Google search engine from merely word matching to a more intelligent network-form model, namely a set of vectors consisting of a tremendous number of pairs of entities and all kinds of relationships between them. An entity in a knowledge graph can be anything verbally represented. A vector has to be a fact that is ensured by processional opinions or statistics; it is set up by a group of experts or extracted from a vast bulk of verbal articles on training data sets like World Wide Web. The main difference exists between the the knowledge graph approach and method of cognitive mapping lies upon distinctive goals of respective methods. In more details, knowledge graphing pays attention to knowledge as a social fact (Durkheim, 1938) filtered by statistics on a large number of concept entities and relationship pairs and well-agreed among the mass-population; it is built as a network-structured library that can be searched for rather stable and objectified knowledge. By contrast, cognitive mapping reflects the unstable, ongoing and individualised understandings of individual persons; the maps are highly subjective. In fact, one of the most important applications of comparisons between cognitive maps is to figure out these different meanings of words and links. Moreover, as mentioned at the beginning of 2.1, it is impossible and luckily unnecessary for all IDCT participants to come up with a shared knowledge system, not to mention an universal common ground; with merely a structure of knowledge sharing, as cognitive mapping has shown, it is already possible for people to communicate and collaborate with each other. What can be borrowed from knowledge graph is a set of technology that enable to visualise a cognitive map directly from interview reports; with the help of natural language processing, cognitive maps can also be collected automatically if every scientist writes down self-reflect understandings on the project regularly in research notes or dairies. It is admitted that this complicated technology has not been implemented in this dissertation; cognitive maps are collected via sociological interviews rather than computer technologies.

2.4 A method of inter-subjectivity

2.4.1 Inter-subjectivity

The method of cognitive mapping discussed here is also inspired by the ontological turn that happened in anthropology (Descola, 1986). Collecting cognitive maps is different from photo-taking or mere scientific observation. Rather, cognitive maps are 'local knowledge' in an anthropological sense, to be constructed through an interactive process between the investigators and informants. Though the investigator's role is more supportive than constructive, both sides need to try to reach agreements about what elements in the cognitive map mean. Therefore, the process of drawing the map and making sense of the drawings is inter-subjective. Even though only informants themselves, rather than investigators, have the right to explain or judge on the 'correctness' of the investigator's understandings on the IDC collaboration the informants participate, the investigator is allowed to interpret the elements of the maps and the follow-up interviews. After all, informants have to make the interviewee understand on the map they draw.

This 'free-style' drawing with no restriction on the number of the nodes and the content of the map helps to present a relatively down-to-earth landscape of the informants' minds. Thus it is quite different from those cognitive maps drawn under a clear requirement of the outlook of the map or of a fixed number and shape of nodes. Such a 'free-style' drawing matches with the expectation of the IDC team members, who insist on their autonomy in presenting their projects in a way they feel comfortable. Indeed, in the process of drawing, when I tried to intervene and ask for more details, here were some of their immediate responses: '*But you said only me has the right to decide what I draw on the map*.' '*I believe this activity is more important than any other else. So I won't delete it from the map even though it is not a scientific term*.' '*I draw as few as I wish. If you want me to explain clearly every detail of these notions, it will take me hundreds of hours. But I don't have so much time and I believe that the notions I draw here are enough for you to understand our project.*' Apparently, their satisfaction on having the whole right to express their own ideas turns me into a 'loyal' listener, a role that makes my entry into their research life more easily, rather than a critical investigator.

2.4.2 Scale and degree of abstraction of notions

The problem of semantic fuzziness may be caused by informants' drawing maps in a rather 'free style'. This problem is presented in two perspectives: one is various scales of notions, the other is multiple degrees of the abstraction of notions.

To further explain, a notion of smaller scale is constituted around concrete examples, operational details of experiments and specific context, compared with the one focusing on a greater population or more universal issues. For instance, the concept of 'social network' is tuned into a smaller scale one if a researcher claims it as the 'network of students', or even more concretely, 'the network of freshmen students (2019–2020) in a specific university'. Definitely, freshmen students (2019–2020) in a specific university is only a small component of students, thus is a group of smaller scale. Whilst a notion of a lower degree of abstraction consists of more phenomenal facts or constructions rather than theoretical scientific terms. For example, the concept 'human mobility' is a higher abstracted than the explanation on the phenomenon of 'people follow each other and take moves on the xy platform'.

These two properties of notions are inter-related. For instance, the notion 'Facebook' is considered both less abstract and on small scale, compared with the abstract and larger scale notions like 'social network' in the sense of sociology or 'developmental biology'. 'T1 process' is a notion rather abstract and small scale, because this term represents a transitions process 'consist of two phases: (1) collapse of a junction with dorsal-ventral orientation (vertical) with fusion of two 3x vertices into a single 4x vertex, (2) expansion of a new junction in anterior-posterior orientation (horizontal) in perpendicular orientation by splitting of the 4x vertex into two 3x vertices' (Kong et al., 2017: 15). And 'academic incentive system' may exemplify the large-scale notions that are less abstract.

The great distinction between notions with various scales and degrees of abstraction influences the fluency of interdisciplinary communications. Leo, the biologist introduced in 1.1, told me,

'There is always a process in which our collaborators and we find a way to understand each

other. At the beginning I wanted to tell Albert (his collaborator, a statistician) goals of our current study, but he repeatedly described me the very details of those mathematical equations...you see, I tried to discuss with him about the context of our project from up down, but him bottom up. Then gradually we recognised this problem and discussed a lot, until we had fulfilled a middle way: none of us goes into very details into one's own discipline unless needed, nor do we talk about very general common goals. Now we just discuss what specific experiment I have done, what kind of results he can get or has already got from this data analyses, and what's the next. For example, I only need him to tell me that he will conduct trajectory analyses on nucleus of the cell. No more details. So normally this is also the contextual level I speak with you and draw on the cognitive maps.'

In fact, the same problem may occur when my informants are explaining their cognitive maps to me. They can hardly go into very detailed terms, which require a lot of expertise in specific scientific areas. Yet if they merely talk about very general notions, it is hard for me to understand them. Thus they always choose to tell me whether the notion they draw is in large-scale one and most of them choose to show me notions in the middle degree of abstraction which are enough to make their ideas understood. Luckily, my informants told me that they communicate with collaborators from other disciplines also in the middle degree of abstraction like they share with me.

2.4.3. Limitations of cognitive mapping

Two obvious shortages of the method of cognitive map can be found. First, it is too time consuming. This kind of map drawing is conducted three times for every IDC group. Suppose I am able to be lucky enough to spend the whole week finishing interviewing all members of one team, and to spend my full time investigating different teams before the second round, I am able to collect data from around six to eight teams in parallel in seven or eight months. Then in two years I will get at most twenty-four cases, which are still a quite small number for sampling. In fact, making appointments with 'busy' scientists are much harder than one can imagine.

Second, it is worth noticing that limited information on lines of cognitive maps has been used when they are transformed into networks by the software of UCInet. Indeed, this method is far less mature and will be further developed in the near future.

Chapter Three

Cognitive Mechanics of Knowledge Interaction

With research target set up and methods developed in Chapter Two, Chapter Three and Four will elaborate how knowledge interaction in interdisciplinary collaborative teams (IDCT) is operated at two interrelated levels: *the cognitive level*, which takes place in intra-personal minds (Chapter Three), and *the interpersonal level* (Chapter Four), which is about the organisation of workflows (see figure 1.3).

In order to tease out the processes of forming an IDCT from the cognitive level, section 3.1 focuses on the emergence of 'boundary objects', which are specific scientific notions linking different research areas that are discussed and exchanged between scientists trained in different disciplines (section 3.3). It then discusses the instability of these boudoirs objects in the progress of collaboration (the section 3.4.2). Ultimately, this chapter revisits a previous question posed by Dai and Boos (2017) 'how much sharing is enough' by introducing the elements of time in considering the long-term dynamics of knowledge sharing process. Informants in this chapter are senior researchers, namely professors and PIs, arguably the core group of scientists in IDCTs. Basic fieldwork information is introduced in section 3.2.

3.1 Shared Knowledge

This chapter sheds light on the content and structure of scientific knowledge that is interacted, namely shared and transmitted from one person to another. In the cognitive level, knowledge interaction is an issue at stake for the discussion on the extents to which a consensus can be reached on understandings of the joint project in interdisciplinary collaborations.

The boundary objects (Star and Griesemer, 1989) and the epistemic links (Laudel and Gläser, 2014) have been deployed to partially describe the process of knowledge sharing. By definition, boundary objects refer to the minimum sharing of cognition between people, requiring at least one physical or abstract object and a common identity on it; and epistemic links describes an extent of connecting personalised knowledge into the shared knowledge of a research area. They are targeting at slightly different perspectives in terms of the degree and content of the epistemic consensus among people. However, they emphasise the same essential tension in an IDCT between the needs of keeping heterogeneity of various professional rules and ways of thinking in the respective disciplinary research communities and of surpassing disciplinary boundaries in order to integrate different ideas and research methods (Laudel, 1999; Turner et al., 2015).

3.1.1 Boundary objects

Boundary objects, according to Star and Griesemer (1989), refer to not only physical objects but also abstract objects like concepts and events. In a classical sense, a boundary object is defined as ‘abstract or concrete objects, whose structure is sufficiently common to several social worlds to ensure minimum identity in terms of intersection whilst being sufficiently flexible to adapt to the specific needs and constraints of each of these worlds’ (Trompette and Vinck, 2009: 6). From this definition, we may deduce two features of the notion: linkability in the sense that boundary object has the potential to be the keyword connecting different research disciplines and areas, and flexibility, in the sense that it has a wide appearance in different disciplines. A boundary object functions as only shared identity in terms of an intersection, rather than common understandings of people. In other words, a boundary object may have distinctive meanings in different social worlds. But these meanings should be able to be translated through the boundary object among at least two social worlds (Star and Griesemer, 1989).

Wesselink (2009) deployed this concept specifically to the context of interdisciplinary collaboration and implied, though unknowingly, that the type of boundary objects for IDCs should be constrained by an extra condition of shared meanings. In particular, besides to fulfill the two features mentioned above, a boundary object for an IDC is supposed to be a consensus that at least two participants of the joint project share the same understanding of. In Wesselink’s case study on the project called ‘Integrated Assessment of the river Meuse (IVM)’, she examined the formation process of the concept ‘landscape quality’, a boundary object shared by various experts, ministries and administrative and political bodies in the Netherlands. This concept had not been clearly defined until the participants set up the landscape quality framework consisting of descriptions and pictures on eight sections of the river Meuse valley with different characters. Through this framework, the landscape quality was defined no longer as merely ‘an optimum allocation of land use functions’ nor as ‘a purely individual esthetical appreciation’ (Musters et al. 2005), but as a combination of both ‘the judgement of aesthetic values as well as the evaluation of relative importance of landscape functions’ (Wesselink, 2009: 409).

In Chapter Two, and Dai and Boos’s book chapter (2017), we have also elaborated that without the sharing of understandings of a certain notion, it is impossible for scientists to establish an IDC team.

A graphic network of notions helps to tease out the structure of boundary objects. For example, Wilson and Herndl (2007) designed the knowledge map to facilitate IDC projects. A knowledge map includes the common target, so called mission success, followed by several interconnected parts, steps and functions that should be worked out by each group of IDC participants. A knowledge map not only shows a boundary object, but also serves as one. It is constructed by all IDC participants during their group discussions, thus it plays a role of a common goal, or shared flow chart. Thus in order to read the map, people may identify at first which part of the work is taken over by him/herself. By finding the position of one’s work on the map, he/she may easily understand what would be the relationship between his/her work and others’. In this vein, Wilson and Herndl succeeded to deploy knowledge maps to help scientists to exchange ideas and to fulfill the collaboration by guiding them work on their joint project by the map constructed together.

That said, still, people in each research group may interpret the meaning of nodes in a knowledge map in different ways. Also, different from individual-based cognitive maps, knowledge maps are group-work flow graphs. Thus, compared with cognitive-map-illustrated knowledge sharing, knowledge maps work merely as a loose boundary object rather than as a means revealing details of how personal knowledge is run and shared among a group of scientists.

3.1.2 Epistemic links

The notion 'epistemic links', though deployed in existing literature (Laudel, 1999; Laudel and Gläser, 2014), has not been clearly defined. This notion generally refers to relationships between a scientist's research content in his/her process of knowledge production and the current research content of other community members, that is the research field. These relationships are formulated as whether one's research provides rich opportunities to other researchers of the academic community and whether one's project is following the mainstream of the research area. In this vein, to establish the epistemic links requires an awareness of the overview landscape of the research contents in a certain community he/she belongs to. It implies that the concept of epistemic link concerns knowledge connections more on a macro-level than the knowledge sharing which, as examined in this dissertation, is taking place between a couple of scientists' minds. In this regard, knowledge sharing offers a way of specify what exactly are epistemic links and how they change dynamically, which is not mentioned by Laudel and Gläser's works.

3.1.3 Shared knowledge and its visualisation

The knowledge that is shared may be an overlapping of two scientists without changing their respective original points, or an integration of two similar ideas. It functions as the boundary object in the context of IDC. The structure of knowledge that is shared between scientists' minds has been shown by Dai and Boos (2017, 2019). Summarised from factors of the process of scientific knowledge production, which are terminology, methodology and epistemology, we have defined two IDC research patterns characterised by two dimensions: first is the research topic and second is the same research procedure. In particular, in the theory-method IDC pattern people share the same research topic but differ in their research procedure, and in the technical IDC pattern people share the same research procedure but differ in their research topic. Research topics refer to the sub-topic of the theme people are working on. And there are two kinds of research procedures:

'Theory-initiated research procedure begins with hypotheses derived from the literature or past research, followed by research design and data collection. In this procedure, data is collected and analysed to test the hypotheses. Data-initiated research procedure starts with observations and data analysis, followed by hypotheses formulation and data collection, an expansion or rejection cycle of the hypotheses, and ends with a more or less general theory.' (Dai and Boos, 2019:)

We have argued (Dai and Boos, 2017) that these two patterns of interdisciplinary collaboration call for distinctive structures of knowledge sharing. In the *theory-method pattern*, people need to share a structure of knowledge, namely several notions as well as the same causal links between those notions. By contrast, in the *technical pattern*, they merely need to share one or several isolated notions.

However, there are a few extra things to be further developed from this approach. Even though we intend to answer how much knowledge sharing is enough for building an IDCT, we are not in a good position to prove that these two degrees of knowledge sharing are the minimum requirement for a successful collaboration. Furthermore, as the cognitive maps shown are based on a particular stage of the long-term collaboration, which eventually lasted for one and a half year.

In this chapter, I would like to extend the initial problematisation presented by introducing the dimension of temporarily. In other words, this chapter will illustrate the whole process of the development of shared knowledge among group members in 'CSP'. Only in this way can we check whether the degree of knowledge sharing found in the book chapter is the least requirement for building an IDCT or not, and examine the problem of instability of this shared knowledge.

As Star and his colleagues have emphasised (Star and Griesemer, 1989; Star, 2010), the structure of boundary objects should be flexible and shared by people using them. However, quite few of prior researches have illustrated the dynamics of boundary objects. In particular, when notions as shared knowledge play the role of a boundary object, how these notions are structured, shared and changed over time are key issues that has not been well understood. In this chapter, by deploying the method of cognitive mapping, we are able to not only reveal the structure of boundary objects, but also visualise how people construct them and embed them into their own knowledge systems. We will also show that with a certain structure of boundary objects unfulfilled, the collaboration is eventually dismissed.

Before we go into details of how knowledge sharing is fulfilled, it is necessary to at first introduce basic situations of the fieldwork where CSP is investigated.

3.2 A case study: the 'CSP' group

As briefly outlined in 1.6.1, my participant observation on the 'CSP' (computer scientists, social psychologist and physicists) group went through three stages: one semester's weekly seminars (2012–2013), one semester's group discussions (2013) and one semester's collaborations (2013–2014). The kick-off meeting, the formation of specific research topics and setting up research agendas lasted the first two semesters. Whereas in the third semester two research teams were established and worked on specific joint topics. One main reason of the delayed establishment of collaborative teams is due to various problems they encountered during all three stages, such as informants' different research goals, various expectation on the roles and function of potential collaborators, hardness of matching up work procedures, and so on. In fact, scientists are found hardly organise their collaboration and form up a consensus on joint research topics as have scheduled: professors abandoned prior consensus, separated themselves into several groups and based on which they argued with each other; the target specific research themes were easily replaced by other themes emerging via discussions of scientists; expected collaborators were found wish to conduct joint research with someone else. It is not surprising that one problem had not been well dealt with, another emerged. In this regard, the case of 'CSP' is quite representative because they met and finally concurred as many problems as other IDCTs, only others will not face all the problems at the same time like the 'CSP'.

This chapter followed up the long history of the development of the 'CSP' group, illustrating its complexity. In this vein, unlike Klein (1990, 2005) and other prior studies (Clark and Brennan, 1991; Selin and Chavez, 1995; Clark, 1996; Jakobsen et al., 2004; Bergmann et al., 2005; O'Donnel and Derry, 2005; MacMynowski, 2007; Godemann, 2008) have worked out, this work is not an abstract protocol design which scientists are never able to follow. In addition, this fieldwork account refuses to explain merely the aspect of chaos and uncertainty of an IDC's establishment by employing the concepts of emergence (Klein, 1990; Newell, 2001). Even in complicated collaboration processes, people have to go through two substantial processes, namely contextualisaion and integration of knowledge, in order to define shared topics and establish IDC teams.

My involvement in the ‘CSP’ group started from the beginning of the project in fall of 2012. In the group meeting, I was known as a Ph.D student who was interested in understanding the formation of interdisciplinary research groups; I did not present any idea during their discussions, only sitting in their group and recording what I was observing. On a pleasant morning in the fall term, the kick-off group meeting took place in a seminar room at the Institute of Informatics. This meeting was joined by experts on computer science, sociology, psychology and physics from the same university. They had known each other before this meeting.

As agreed a long time ago, research topics of the first stage seminars were set as the following two parts. The first and fundamental part focused on the notion of ‘social network’. In this part people discussed how social networks were understood from the points of view of computer science, sociology, psychology and physics, respectively. The second part was to develop some online applications from a theoretical investigation on ‘social network’, which included three inter-related topics, the networks of software design, the networks of epidemiology, and the networks of social trust in online-offline interaction. These topics, mainly revolving around the IDC participants’ research interests and past research experience, were proposed and prepared beforehand.

After the kick-off meeting started this series of weekly seminars in the fall semester. At the end of that semester, specific and concrete topics were expected to set up by the IDC participants. Indeed, ‘specific’ and ‘concrete’ were two words repeatedly emphasised in nearly half of the ten group meetings in that semester. However, what do these two words mean were still not so clear by that time; as far as I know, many ‘CSP’ members as well as myself showed confusion.

At the second semester, various theoretical and technical offers and demands are claimed, exchanged and matched among team members around. During this semester, the group focusing on the network of software design was the only one that had substantial progress. Yet they refused me from participating in their group discussion. However, by the end of the second stage, none of those three prepared topics claimed half year ago were selected as the main research theme of the IDC group. Instead, two new research topics that seemed utterly different from the above-mentioned three topics appeared at the end of second semester: the ‘Leadership–Followership interaction’ (by a computer scientist, a physicist and a social psychologist) and the ‘Facebook opinion leadership’ (by a computer scientists and a social psychologist).

At the third semester, scientists participating in ‘Leadership–Followership interaction’ eventually started to design new experiments, parameters and simulations. However, it collapsed half a year later. By contrast, senior researchers of the ‘Facebook opinion leadership’ team started by the co-supervision of a bachelor student, who was assigned to work on the aforementioned topic. It turned out to be a successful collaboration. However, after the student graduated, the project ended there.

What makes the success and failure of the interdisciplinary collaboration within the ‘CSP’ group? What are the potential cognitive challenges that occurred in the process and how did people face those challenges? The next section will carefully analyse the ‘CSP’ group as an example of the progress of a typical non-institutionalised interdisciplinary project that is free-floating with not so much time and funding constraints.

3.3 Building up the shared knowledge

3.3.1 Contextualisation

Generally, a research topic is believed specific or concrete only if it makes sense to participant scientists. However, in general, people trained in different knowledge systems in respective disciplines may not be able to understand each other because of great distinctions in their perspectives and concepts for observing and analysing certain phenomenon and in their goals of researches. Indeed, to come up with a concrete topic at the beginning is usually very difficult and rare.

Pioneers who can break through the boundaries among disciplines by simply telling a story in a plain language are always welcomed. For example, an epidemiologist may describe his/her research topic on the relationship between social networks and flu spreading by telling this fabricated yet quite representative story:

One day in the winter, suppose your elder son gets a cold. At the beginning you may think that it is just normal because children get colds in winters. But perhaps suddenly you remembered that another boy in your son's kinder garden was sick as well. Quickly your younger boy was infected as well. After two weeks' fighting with the flu virus at home, the elder brother can finally go back to his kinder garden, finding that one third of his classmates and two of his three teachers are absent in the class because of the flu infection. Unluckily, soon your elder son finds that his classmates are continually infected by a new kind of flu virus, which is found being brought from himself, who was infected by his younger brother, who brought this new virus from younger brother's kinder garden...By telling this story, he/she may conclude: so different kinds of flu viruses spread via face-to-face interactions of humans. People's interactions, no matter in classrooms, in homes or on the streets, can be represented as a social network. By following up the social networks of people who infect flu virus, we are able to illustrate the trajectories of the decease spreading. By studying the structural and dynamical properties of these networks we can set up strategies of controlling the spreading of virus...

Such approach of narrative is a perfect example to illustrate the process of contextualisation by using plain language in the IDC discussions. The key is to unpack the processes of conceptualisation and operationalisation of a specific concept used in a certain discipline, namely in what theoretical backgrounds and practical contexts one discusses this concept, what kind of phenomena a scientific concept is deployed to describe and how to measure or observe this phenomena. In this way, a scientist makes him/herself understood in order to co-produce a common ground that he/she can collaborate with other partners. In other words, to understand what each other actuality talks about is the first step for the sharing of knowledge.

For example, in the case of 'CSP', Kate, a sociologist, was the first one who explicitly talked about topics being 'specific' or 'concrete' and explained them clearly. The discussion of 'to what extent a research topic is specific enough for a collaboration' took place at the first 'CSP' seminar, which was also the second 'CSP' group meeting. Before Kate made her comments, Weiss, who was a computer scientist, briefly introduced topics related to social networks, and discussed with Yann, a physics scientist, about online-offline network interaction studies.

After carefully listening to them, Kate responded:

'For me, the first thing I will consider about online and offline [research topics] is what is the question we are interested in? Are we interested in how offline changes or has been changing

with people being more involved in online social networks?...I think we really need a ***specific research question.*** *I think to know where we should look and what we should, I think, research. I mean, for online friendships and offline friendships, there might be some correlations in some cases which depend on the contexts and so on, but it is still not* ***specific*** *enough'.*

Then Kate explained the kind of research topic that could be regarded as concrete:

'*What came to my mind is thinking about original studies that students could do, or maybe someone will have some preliminary ideas. So you can start with students who just started university here. Typically we except that they just come from our university. They build up new offline relationships. And one could study how this offline and online networks interact or whether these offline social networks come from online social networks...or [you can] study some kind of exclusion and inclusion processes. Or whatever. These are only preliminary ideas to think about, and it is really so hard to study these. I really doubt that [if] we have only online information...as somebody has said, of course, you can get little hints on how people may interact offline. But this is only part of the picture. And I think you need to study, well you want to find out how these individuals influence each other but not on the online platform. Then you could study something that is interesting.'*

Martin, another computer scientist, followed, '*And what do you want to reach with your research? This is a very general thing. You need to say what is the purpose of this research.'*

'Yeah!' Kate agreed. '*Online-offline is correlated, yes. But so what? Why is it interesting? Because of a strategic model or in order to answer a practical question? Or social inequality question? Or whatever?'*

Yann explained that when he was talking about social networks, he indeed had a specific research project in mind. Then he continued to introduce a research project that he took part in. It was a project about studying the mechanics of human mobility by tracing the daily movement of freshmen from a university. It was a research work which by the time, his two students, Ernst and Chris, had completed data collection and started their preliminary analysis of the data. Then Ernst presented his project, carefully with information including the target groups, main activities of freshmen observed, methods of data collection, basic features of their activities found so far, among others. Ernst presented his research in a way that no sophisticated concepts from physics were involved. They also mentioned that at that stage, what they were lacking was a theory to systematically explain and interpret what they had found.

After hearing that, Kate claimed that she could help to explain and interpret their result by sociological interviews. She happily said: '*Well this is very important information! We [sociologists] can ask people what they do after [online chatting]*'.

Then Ernst further explained that as a physicist he saw the certain movement of freshmen from a certain university from the data, what he wanted was to know why people moved like what had been shown by data analysis. Kate immediately appreciated that information and added that this was a good question. Ernst continued to discuss his hypotheses and mentioned that he hoped to find a suitable sociological concept to lay the theoretical foundation. Kate said: '*Yes! This is really an interesting question*.'

Apparently varied were the attitudes among 'CSP' participants towards Kate's keen focus on concrete questions. Yann and Powell were quite data-driven in their research procedure. They told her that without any data nobody cared about what these freshmen did. Weiss, on the contrary, agreed with Kate by emphasising that they computer scientists could process every set of data, but the question was ‘*what to analyse*’. For Kate, physics terms discussed by Weiss and Yann, like curves and degree distributions, did not make any sense. What Kate needed as a potential boundary object was a simple story about the facts that they would study. Therefore, it is necessary to deconstruct compact research agenda and make the topic as explicit and contextualised as possible so that even a layperson with no training in the respective discipline can understand. This supposes to be the initial step for all interdisciplinary collaborations, unless some IDCTs have fulfilled the establishment of the epistemic common ground.

3.3.2 Integration

Furthermore, the second part of the process of boundary object formation is knowledge integration, in which people list their potential offers and requirements, followed by matching them up with each other. These offers and requirements may consist of abilities of dealing with certain kinds of data, theories that may interpret findings from data analysis, terms being able to conceptualise a sort of phenomena and so on. The integration of them does not work when people take for granted in dividing their academic works; it is found that integration has to be based on the achievement of contextualisation, because only then are scientists able to understand each other and gear their needs. Thus it will not be a surprise that this integration process may take several rounds of negotiation, which involve contextualization and re-contextualization of the specificity of the research contents.

Stage 1: A taken-for-granted division of work

The project of Facebook Opinion Leadership provides a perfect example. The first round of integration of two sources of expertise from Kate the sociologist and Steve the computer scientist took place not long after the birth of the project. It started with the potential research topic of ‘networks of social trust in online-offline interaction’ (‘trust’ group hereafter). At the beginning, it was agreed that Steve collected and analysed the data about online interactions of people, and Kate conducted offline survey on those who were building or cutting trust relationships with offline friends in parallel. This arrangement immediately met a problem, which was about the different understanding of the notion ‘trust’. Kate suggested in the meeting: ‘*I would suggest that the whole group read a text and discusses about that together because we have such different understandings about what we are doing. Almost everyone talk about ‘we use sociological concepts’* (everybody laughed)...*Besides, trust is also a psychology term.*’

Stage 2: Re-defining the key concept

The subtext of what Kate suggested implicitly was that everyone claimed that they used so-called ‘sociological concepts’ without understanding the real definition and context of these concepts in sociology as well as in social psychology. Nevertheless, others did not accept her suggestion, as no one would like to abandon their own scientific definitions on trust. Consequently, in the following seminars, each participant introduced basic ideas, concepts and literature related to ‘trust’ in his/her own discipline to the whole ‘CSP’ group.

At the third group meeting, Kate introduced her understandings of ‘trust’ deployed in the studies of social networks. She suggested the perspective of embeddedness[10] was a good starting

[10] The paper Kate mentioned is Granovetter, M. 1985. Economic action and social structure: The problem of embeddedness. *American Journal of Sociology, 91(3)*, 481-510.

point, as in that perspective, trust facilitated economic exchanges and that trust was generated by long-term interpersonal relationships. In this vein, she mentioned that trust could be treated as a kind of social capital, the reputation resource of being trustworthy which was deeply based on social networks. Then she proposed two topics based on two articles, one was about agent-based modeling, and the other was to study online social networks. However, questions people asked were neither about online-offline interactions nor about trust. Instead, participants asked a lot about concepts such as capital, social mechanics, the theory of public goods and technical issues of operationalisation, such as how to collect whole network data. The followed discussion was driven away from Kate's initial attempt, i.e., introduced how 'trust' was defined in sociology and upon which what kind of conclusions had been made by sociological studies on 'trust'. Her brief introduction was necessary but not simple enough to show the process of contextualisation and operationalisation of the term 'trust' in the discipline of sociology.

Surprisingly, Steve realised the importance of sociological treatment of the team 'trust' and began to read sociological literature and conceptualise the 'trust' term in computer science. In the interview, he showed precise understandings about how different levels of trust could be built up as a reputation system based on interpersonal relationships and how online and offline social networks were interpreted from perspectives of both computer science and sociology. He said,

'*The online social network...is basically driven by the underling architecture. How it is implemented, how it is constructed, what do the links mean, how can you expose yourself technically...I mean the platform is behind the social network. So what can be the possibilities? Do I have to exhibit my information to other people, how can I constrain it to the groups of people, or how can I define a circle of friends, these kinds of things are technical issues that be implemented and you can use them. But I think lots of people don't know it very well.*

Well, the offline social networks, there are a couple of well-known social networks in the society. For example, people that graduate from the same university, they form an alumni network. Graduating from the same university is the connection among them. Maybe there are stronger links to someone compared to other ones depending on how many transactions you have with them. Transactions are not in the technical sense but meetings or something like that. Maybe someone is your boss and graduates from the same university. This is a strong link of course. There are different types of links...There is also all-boys network...In China, there is guanxi.'

He had even developed insights into the Chinese notion of *guanxi*, a sociological concept describing personal relationships and interpersonal networks between Chinese people (Gold, Guthrie and Wank, 2002). Moreover, he already had innovative ideas in evaluating and calculating trust (trust chains) between people and devices like a car run by a computer operational system.

'*Why do people trust in devices? This is the topic I want to collaborate with Kate. We have not met to discuss about it, but hopefully we do in the seminar. Also I would like to talk to Marilyn about opinion leadership because psychological things are also involved here.*' He continued.

Certainly, the trust between humans and devices was potentially related to online-offline interactions because people might build up reputation systems among offline social groups, and devises were essentially the physical location on which online social networks were based. In other words, Steve's trust story could be a potential boundary object, because it was plain enough to be understood, complex enough to be interpreted by both computer scientists and sociologists, and the mechanics of trust was concrete enough to be set as a common goal.

Stage 3: The integrating process

The discussion between Steve, Marilyn and Kate was supposed to bring some light on the term 'trust' so that research demands and offers could be matched and a sub-group could be formed. But it did not happen until the February of 2013, three months later after the last weekly seminar took place. It was a meeting in which Powell the computer scientist, Yann the physicist and others also took part in. Eager to reach an agreement on the meanings of the term trust with Kate and Marilyn, Steve was very active throughout the discussion. When every one of the 'CSP' group was asked to propose potential collaborative topics, he presented a very clear scenario about this 'people-devises trust' topic: '*Our interest is in trust reputation. I also heard this trust reputation in Kate's and Marilyn's talk. And there must be some influence from your area. Why are computer scientists interested in this topic? Actually it has emerged from the computer security area.*'

'*And also online purchase area.*' Powell made a supplementary explanation.

'*Yes.*' Said Steve, '*but the key is security, but not in the heart sense. It is about the security that you want to interact with people or things but you don't know whether you can trust them or not. And it increasingly starts to become depended on typical things which we really do not fully understand or fully control.*'

Then Steve further gave an example of smart phones, in order to illustrate how people used this device everyday to contact with people, check emails or record personal information without fully understanding, for example, pin code or password, inside the smart phones. Another example he introduced was Dropbox. He carefully explained different kinds of standards for algorithms of the software to protect individual information security and how reputation of companies were built up by obeying those standards or were destroyed by making program bugs to break those standards.

'*Can we trust on the implication of security that is designed by one company or not?...this also depends on how much we trust what people say (about this implication) and what kind of report they give. As you can see, the whole security areas nowadays, whether we can trust our devises, is very much depending on these issues of trust, reputation, social relationships and actors in this field...And this is a very complex scenario.*'

'*But where could we get research data?*' Interrupted by Powell '*you need to know the interaction [among people and devices] which is inferable for the research.*' 'Yes', answered Steve, '*this is why I find it interesting to collaborate with sociology and psychology because this is something that computer science cannot look at buy itself.*'

Powell wanted to highlight the problem of operationalisation, namely the issues of how to measure online-offline trust with a set of data and where to obtain this set of data. Thus a few minutes later he interrupted Steve again and said: '*but who can capture these interactions? Sociologist [he turned to Kate], I don't think you have the particular means to attract this. You could either use some online developer's forum to see that they have some interactions. That's computer science work. Then sociologists can help to judge whether this is relevant or something. So how sociologist can play a role here? So how can we do this research is not clear.*'

Powell's questions and suggestions had rudely yet successfully changed the focus of the group discussion, which had made others uncomfortable. '*Let's the others say something.*' Yann said.

Afterwards, Marilyn shortly discussed with Steve and Powell about what data sets were accessible. Also, this heated discussion apparently encouraged Kate significantly. She said: '*The* *immediate problem I saw is how to measure trust. I think more about it is a research project now...When I think about trust and reputation, it would a quite nice unified theme for very different research fields. In a way it's about social conditions about trust. The technical side is solved. What kind of social conditions that people trust certain devises or sites...There are different fields that can deal with this topic...or the development of trust in the Internet is the topic. People also do experiments on this topic...*'

Kate then elaborated a lot of potential topics that under the umbrella of the concept trust that every 'CSP' participants were potentially able to establish IDC projects. Yann tried to find out the essential part of the mechanics of trust, as physicists had always aimed to, and claimed that the most important thing was that people had free choice to either trust somebody or not. Steve answered that '*but companies had different reputation which influence people's attitudes*'. Kate agreed with Steve.

The following twenty minutes were well passed in discussions within two separate sub-groups, one between Yann and Powell, and the other among Steve, Kate and Marilyn. The former group cared for how to get access to online and offline data that they were able to put on analyse, namely an integration of data set. The latter tried to defined different social situations where trust play a role in people's choices, such as whether to purchase iPhones or to use Google, that was the integration of concepts in certain context. This topic converging process began when Steve argued that in fact people were affected by opinions, and different groups had various opinions. Yann further suggested the context for a questionnaire to collect these opinions. This then triggered Kate and Marilyn to develop the topic into more details, namely theories, experiments and specific research scenarios about how trust was developed with a network of people and devices. In contrast, Powell became interested in online software that could detect online social relationships. Finally they all agreed that trust could only be established on people's opinion on people, devices and institutions. And Marilyn suddenly made a shift in conversation:

'*Powell, I think our previous little project about opinion leadership on Facebook would also fit because it is to believe somebody and to take opinions, follow the recommendations to this person.*'

In this way, after rounds of heated discussions, Marilyn and Powell succeeded in converging their demands and offers into one specific topic. At the end of that semester, Kate told me in an interview that she refused Steve's requests to work jointly on human-devices trust and chose Yann as collaborator. However, she did not really discuss further with Yann as she was constrained by lots of departmental obligations, such as classes and projects in her own field. Yann then turned to collaborate with Marilyn and Weiss in the Project of 'Leadership–Followership'. Till then, the small projects were born from the 'CSP' group.

3.3.3 How knowledge sharing is established

Complicated is the process of sharing specific sets of knowledge that work as boundary objects. Yet via ethnographic accounts this chapter reveals two processes that people in an IDCT have to go through in order to establish boundary objects.

Like what Kate had done introduced in 3.3.1 and Steve in 3.3.2, contextualisation often starts with a detailed story in plain language about the backgrounds of a certain concept. The goal is to help others understand the issue of what specific phenomenon and objects that a selected concept depicts and in what situations and scenarios a research argument can be claimed. In other words, a concept or a research question becomes understandable through contexulisation. The integration of knowledge, which is the second part of the process, consists of three aspects: the integration between concepts, between data and between concepts and data.

In the case mentioned in 3.3.2, situations where trust plays a role in people's choices were what Steve, Kate and Marilyn tried to integrate from the concept-concept aspect. Their discussions on 'choices' had been further integrated Yann's idea. Thus 'choices' was eventually updated into the concept of 'opinion', one of the conceptual boundary objects shared by Steve, Kate, Marilyn, Yann and Powell, namely nearly all the participants. Indeed, influences to the 'free choice' may be derived from others' activities, opinions or emotions. And the person whose opinions are most trustworthy is called opinion leader. As online data is easier to be collected and analysed, it is not difficult for Marilyn to recall her prior project of examining online opinion leadership on Facebook.

Powell and Steve worked also from the second aspect by discussing how to integrate offline sociological interview data with online data sets collected by computer programs. Data collected from various sources and in multiple ways is integrated, as the second aspect of knowledge integration, when different data sets can prove each other or be transferred to each other.

When Steve, Kate and Marilyn were focusing on concepts, Yann and Powell were trying to find a proper way to collect and analysis online-offline data in order to test the so-called 'interaction' between human and devices, such as people using applications on their smart phone. Thus the third aspect, as between concepts and data sets, concerns an integrated way of operationalisation, namely to measure certain concepts from one discipline with methods from other disciplines.

These three aspects of knowledge sharing may happen in parallel or by sequence. To come up with boundary objects is not necessary to fulfill all three aspects.

Except for the two necessary processes, the establishment of knowledge shared in an IDCT, as these cases also reveal, may not always stick to the initial plan; on the contrary, it may sometimes emerge from a radical change of long-term discussions among IDC participants with no clear intention. As illustrated in the case of 'CSP' group, it took years to set up and discuss the 'trust' issue as a boundary object but only twenty minutes to deconstruct it and develop a new one, namely the concept of 'opinion'. To compare with the first glance on the 'trust' project, it is apparent that in the project of Facebook Opinion Leader, the research context has been partially changed, and people who supposed to collaborate are totally different from what had been planed. This property of emergence fits well with the observations of Klein (1990) and Newell (2001). Both of them claimed that the IDC process was a complex system, in which several components of an IDCT and IDC knowledge formed up a network of nonlinear relationships. Here, nonlinear means the combination of each component of the system is different from a simple sum of them, because there might be feedback loops of both 'positive (enhancing the behavior) and negative (dampening or reducing the behavior)' (Newell, 2001: 7).

3.4 Dynamics of shared knowledge

3.4.1 Instability of shared knowledge

This research claims that identifying overlapped scientific knowledge among IDC participants, namely having well established boundary objects does not ensure the success of an ever-last collaborative group. On the contrary, the shared knowledge develops and changes with the progress of the collaborative project; the cognitive interaction, as a matter of fact, is unstable and dynamical. Here being unstable does not necessarily mean that the projects are discontinued, even though sometimes they do. Rather, there are other situations for example where scientists put their focus to other concepts because they think the already-shared knowledge is not important for their study any more, where they have made the already shared knowledge as a concrete base of their further collaboration and have moved forward to the next step of their joint research, or where they work separately into respective detailed works under a big umbrella of shared concepts. Instability also implies that sometimes they break up before the co-publication comes out, which is usually seen as the end of a round of collaboration. There are possibilities that some members drop out from this project and others come in. In short, the shared knowledge changes by time for a number of reasons.

3.4.2 An example of the development of shared knowledge

How these changes are taking place can be exemplified vividly by a detailed elaboration on the progress of the 'Leadership–Followership' Project. The Leadership–Followership team members met four times during my observation time. Cognitive maps were collected at four stages of their collaboration: one before the first meeting, one after the second because team members did not finish their discussions at the first meeting, and each after every other meeting. Interviewees Marilyn the social psychologist, Weiss the computer scientist and Yann the physicist, the three out of four participants drew their maps. In this way, their cognitive maps show the changing of minds of the informants and monitor the interactions of their minds during group meetings. The only main participant I did not manage to interview was George. Before the formation of the project, he had designed the Honeycomb platform for the human mobility experiments by computer programs. During the half-year's working with the other team members, he took part in the 'CSP' group by mainly introducing the infrastructure of the experiments and providing program codes to Weiss. Nevertheless, it was Marilyn, Weiss and Yann who were leading the progress of the joint project.

Stage 0: rich opportunities before the meeting

Figures 3.3, 3.4 and 3.5 show that since detailed context of the 'Leadership–Followership' Project was still unknown, all of the three informants opened to various possibilities of the project. For instance, in Figure 3.1 we can find that Marilyn divides her map into three interrelated components: under the main research question about people, there are 'areas of applications' to be developed based on results of research questions; there are certain potential fields like 'online/offline interactions' or 'social structures' from which specific research topics come; there are also 'measurement methods' that can be employed to deal with questions in those topics. In each component there are potential collaborative nodes marked in black, which mean that those concepts to be discussed and analysed by all three collaborators. The cognitive maps of Weiss's (Figure 3.4) and Yann's (Figure 3.5) at this first stage are as general and open-minded as Marilyn's.

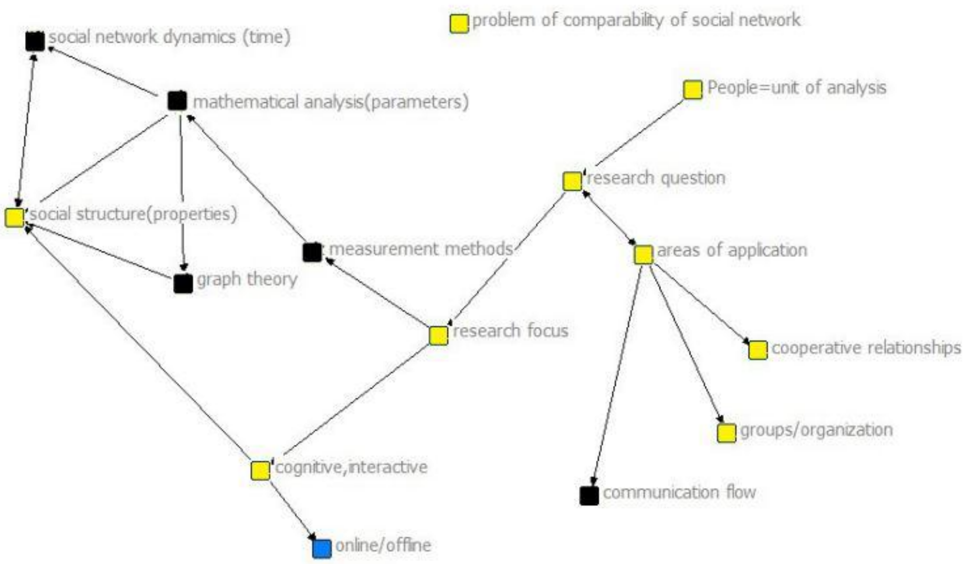

Figure 3.3 Cognitive map of Marilyn at the first stage of the Project of Leadership–Followership.[11]

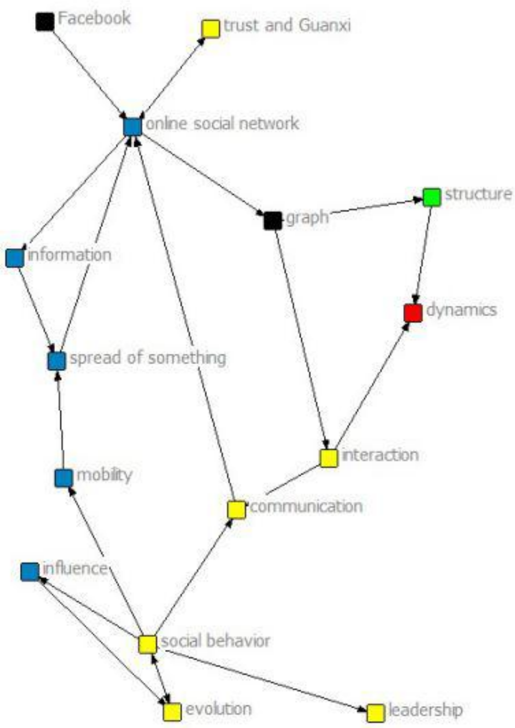

Figure 3.4 The cognitive map of Weiss at the first stage of the Project of Leadership–Followership.

[11] For all figures from 3.3–3.14, Nodes in yellow represent academic concepts from social psychology, in blue show concepts of computer science, and in red, of physics. While Nodes in black represent concepts shared by computer science, physics and psychology; in green, the shared concepts by psychology and computer science; in orange by physics and psychology; in purple by computer science and physics.

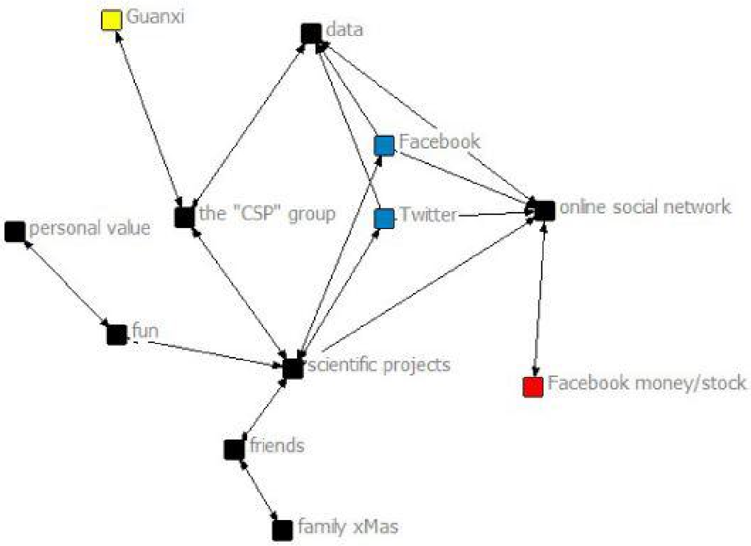

Figure 3.5 Cognitive map of Yann at the first stage of the Project of Leadership–Followership.

Stage 1: sharing of knowledge

The followed first meeting was held just after my first round of interviews. During the meeting, Marilyn and George first carefully described every detail of their previous works to Yann and Weiss. This included a theoretical background of the relationship between leadership and followership, experiment platform, which was called the Honeycomb, control variables and results of measurement and experiment settings like displaying goal fields, in which player could get financial rewards, selection of players, the psychological meaning of these settings, the methods of conducting experiments, the number of people that was set and summoned, results drawn from existing data and so on.

After listening to their introductions, Yann and Weiss asked different questions from their own disciplinary perspectives. Yann focused on specific parameters that Marilyn employed in her experiments and suggested that in physics these parameters could be measured in a different way. For example, he suggested measuring the 'convex hull' of players, from which certain patterns might be found and some physics equations could be in further generated so that enhance accuracy and validity of parameter measurement. Weiss did not talk much half an hour before the end of this meeting. He asked for codes of the Honeycomb platform and a part of existing experiment data, by which he would like to build up computer simulation model in order to understand probable behavior strategies of players, which would lead to the results of movement experiments.

Till then, cognitive connections were established among all group members, which could be clearly seen from cognitive maps at the second stage (figure 3.6–3.8). As already introduced, Weiss had his own goal of developing theories of human mobility. Also Marilyn was aiming to understand her theoretical questions, in which leadership was defined by the leaders' followers. As a result they collaborated in what I term the technical pattern by sharing and comparing the data. Yann provided methods, such as parameters, program algorithm and descriptive analyses.

At the second meeting, based on the experiment data provided in the previous meeting, Weiss showed his primary computer simulation models. It took a long time for the others to clearly understand how Weiss built up these two models. The results excited them, because phenomenon of leadership showed up in his simulations. This implied that the simulation was successful and that they could further make comparison between existing experiment data and the simulation model. This progress was shown in Weiss's map in Figure 3.7. Yann further found that the emergence of leadership might be measured by using other parameters like 'cluster coefficiency', which Weiss could apply to his simulation experiments. Marilyn believed that Weiss's model perfectly matched her insight of defining a leader by followers, which was a theoretical breakthrough in the field of social psychology. She was then inspired to summarise existing data by listing parameters that had been tested in various experiments, and to design new experiments in order to fit Weiss's model settings.

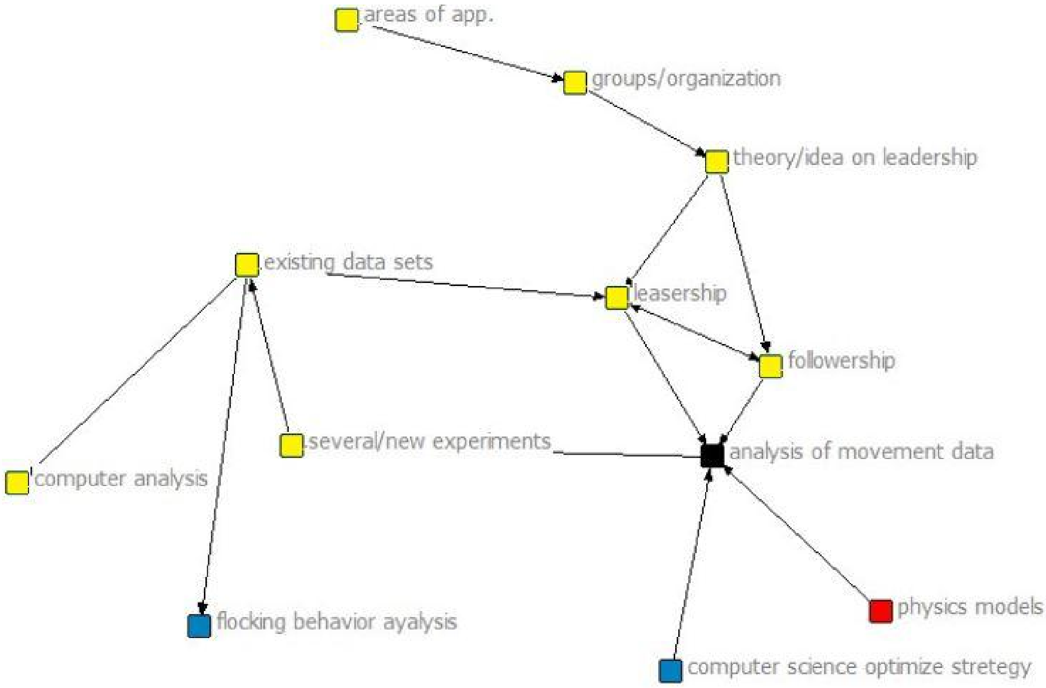

Figure 3.6 Cognitive map of Marilyn at the second stage of the Project of Leadership–Followership.
Note: revised from figure 3.4 in Dai and Boos (2017: 58)

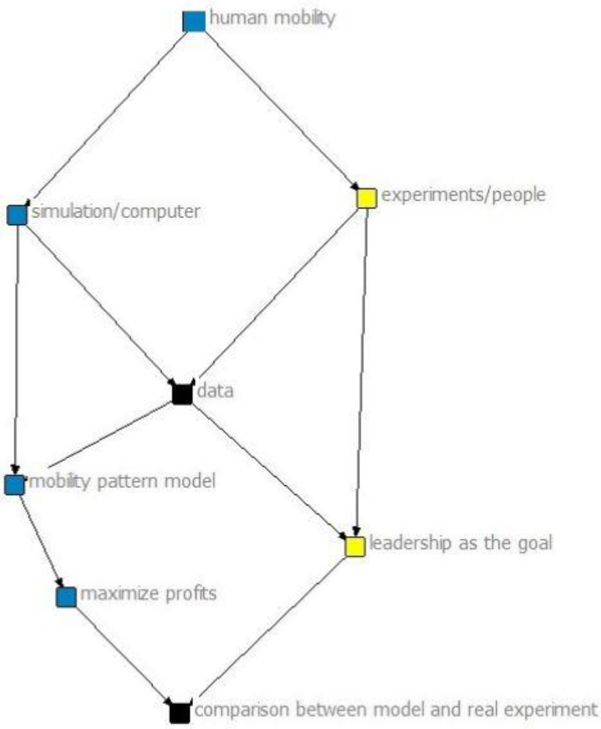

Figure 3.7 Cognitive map of Weiss at the second stage of the Project of Leadership–Followership.
Note: revised from figure 3.5 in Dai and Boos (2017: 58)

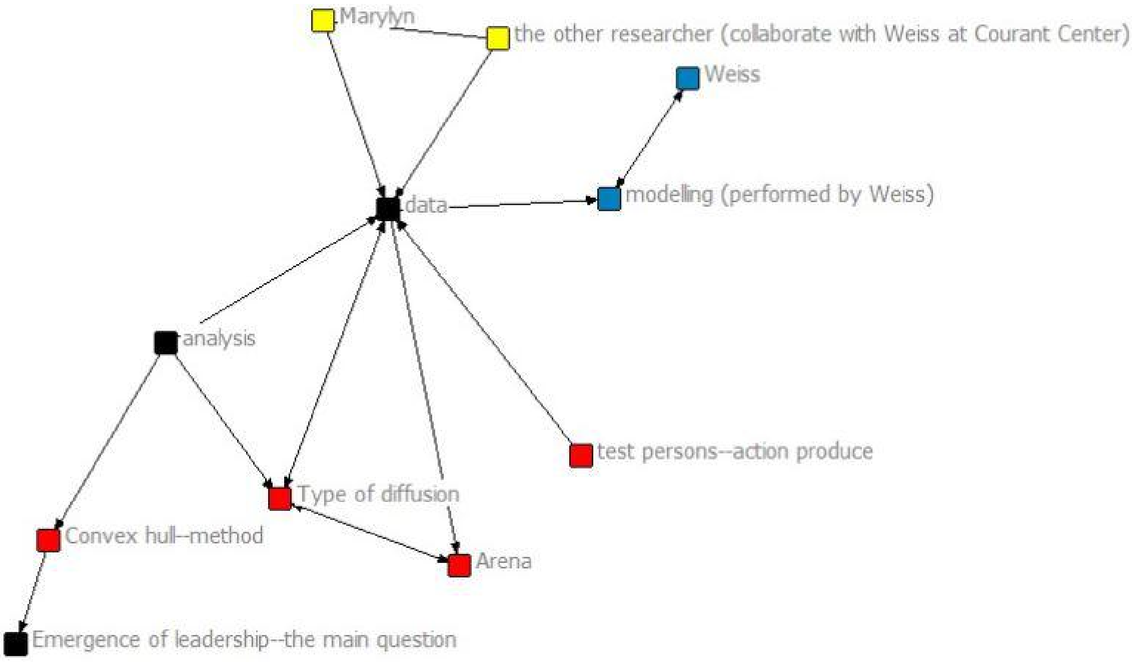

Figure 3.8 Cognitive map of Yann at the second stage of the Project of Leadership–Followership.
Note: revised from figure 3.6 in Dai and Boos (2017: 59)

Stage 2：Go into details
The second stage of cognitive maps revealed how far 'CSP' team members had moved further together. Small converged component of concepts were shown in all three maps, which meant they all started to take care of some specific part of this study. Of course these three focused components of knowledge were quite different in terms of disciplines. In Figure 3.9, as Marilyn needed to input existing data and to design new experiment, her map was illustrating one component of psychology concepts which was linked with another component in which collaborative contents were displayed. Yann's map (Figure 3.11) showed also two components of concepts: on the above there were collaborative concepts which belonged to various combination of all three disciplines; on the bottom physics parameters and papers were listed and connected to each other. Both Marilyn's and Yann's map presented a situation that psychology and physics concepts were generated and linked into computer science concepts as input of Weiss's simulation modelling. This made three out of four percentage of concepts drawn in Weiss's map (Figure 3.10) were multidisciplinary, which meant that Weiss was keeping intense collaborations with the others.

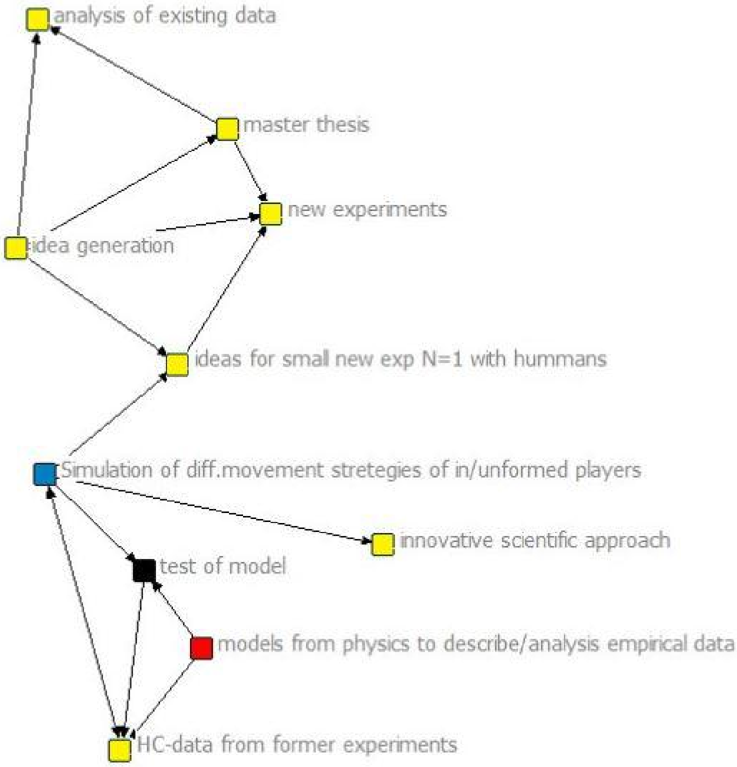

Figure 3.9 The cognitive map of Marilyn at the third stage of the Project of Leadership–Followership.

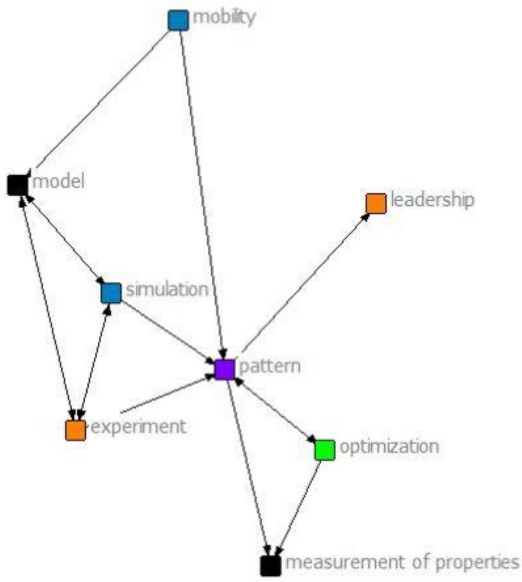

Figure 3.10 The cognitive map of Weiss at the third stage of the Project of Leadership–Followership.

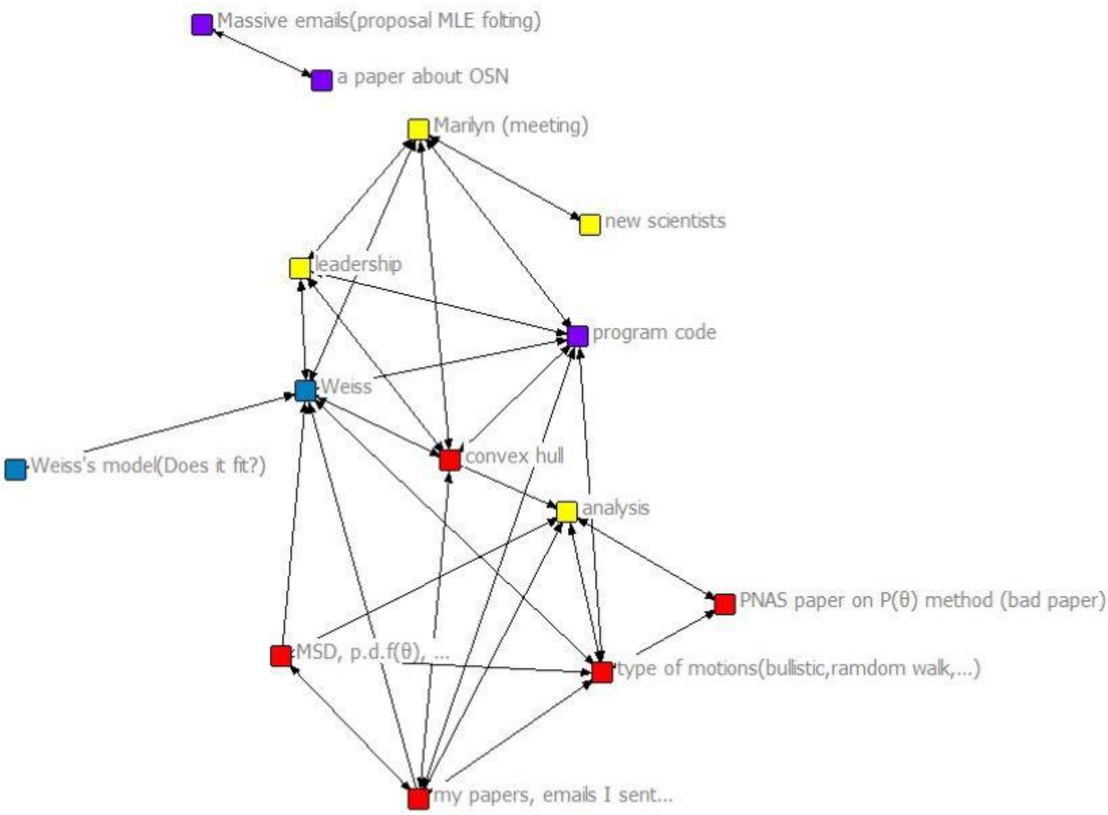

Figure 3.11 The cognitive map of Yann at the third stage of the Project of Leadership–Followership.

By analysing the structure of overlapped nodes between two maps, it was found that Marilyn and Weiss had reached a small structure of shared concepts, which had broken through the condition of minimum amount of knowledge sharing, that was isolated nodes (Dai and Boos, 2017). On the contrary, the shared knowledge structure between Yann and Marilyn and between Yann and Weiss turned to only several isolated nodes, which demonstrates the weakening of collaboration between Yann and the other collaborators. However, if the cognitive map of Yann's at the third stage was compared to the one at the second stage, it could be seen that there were more links between his ideas and his collaborators, which implied that the collaboration was in fact going deeper than last time. It is not a contradictory phenomenon because Yann drew more detailed concepts, such as 'MSD, p.d.f (θ)' and 'type of motions', than Marilyn and Weiss, in whose maps most of scientific concepts were more general than in Yann's. Yann told me that it was because he provided parameters to them, which was already very specific research content, while Weiss and Marilyn needed to take care of the whole structure, which made their concept nodes more general.

Stage 3：disagreements and breaking up

However, communication problems still happened. As Marilyn and Yann were supporting Weiss's simulation model by existing data and parameters, designing of new experiments and building of physics models were then highly depending on the result of Weiss's progress of modeling. Unfortunately, Marilyn made a small mistake by using the wrong email addresses to inform Weiss and me. Consequently, Weiss got in touch with the team one hour after the start of the last meeting, while I only took part in the final discussion part. When recalling this troublesome meeting schedule, opinions differed for each interdisciplinary collaborator. Marilyn told me that during the waiting hour all three members realised that none of them had made any progress during the last week, and they were all waiting for Weiss to present some new results. Finally good results came forth, with successful movement strategies of players found. Moreover, everyone agreed on Marilyn's exciting new definition of leadership. Her cognitive map (Figure 3.12) illustrated that the collaboration was processing from analysing existing data to new ideas and new experiments. She further told me that since everyone was devoted into the new idea about comparing the simulation model and experiment data, Yann's physics model had been 'abandoned'. However, in his interview, Yann denied this statement and told me that he was just waiting for analysing results from Weiss. He wished that Weiss did more quickly as expected. He further complained about the delay of his collaborators. He drew a Christmas tree on his map (3.14) because he guessed it was due to the Christmas that everyone was reluctant to work as hard as before. His map was in turn largely simplified and more indifferent to his collaborators than his former maps. Weiss's map (3.13) shows that he kept a significant role in collaboration by making the important comparison mentioned above. Weiss and Marilyn shared their maps with isolated nodes, but they did not overlapped concept nodes with Yann any more.

After the forth interview, Yann went to Switzerland and Weiss moved to China, which made the investigation end. Three years later, an article was published in a book as the consequence of this IC project. It was written by Marilyn,Weiss and George. And Yann's name was absent.

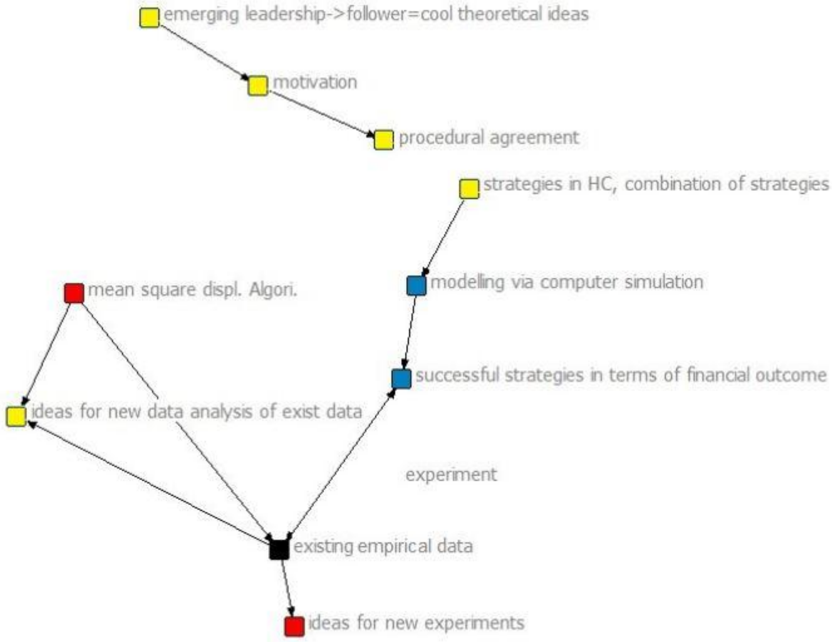

Figure 3.12 Cognitive map of Marilyn in the forth stage of the 'Leadership–Followership' project.

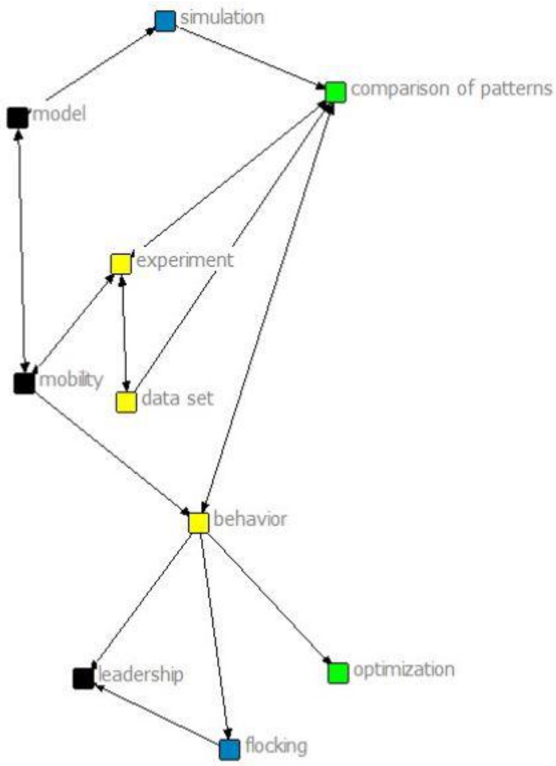

Figure 3.13 Cognitive map of Weiss in the forth stage of the 'Leadership–Followership' project.

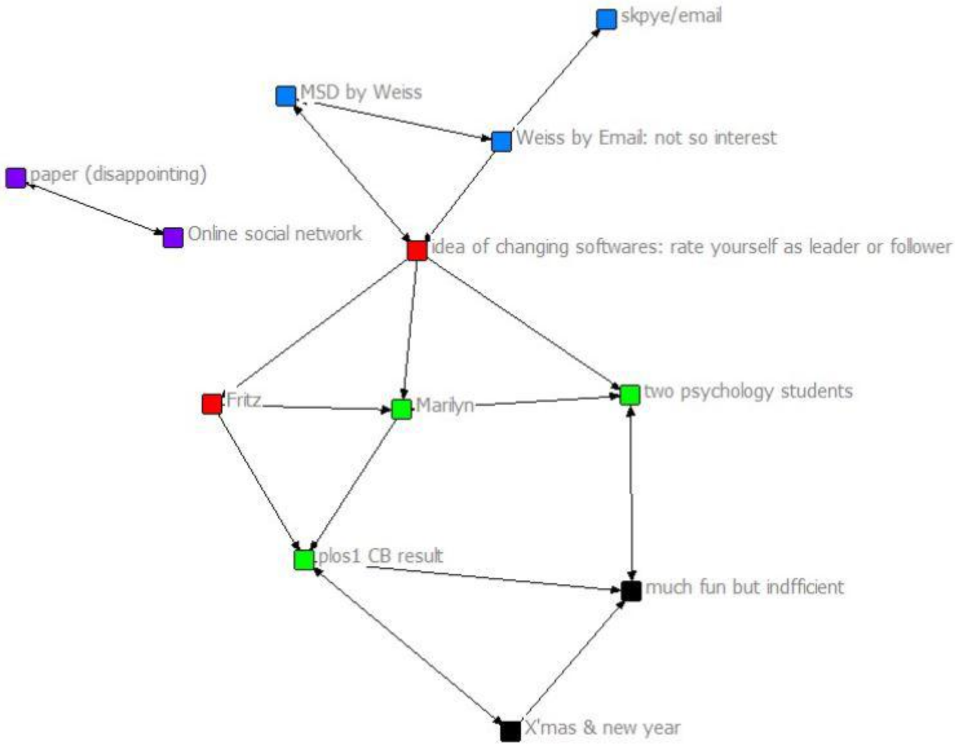

Figure 3.14 The cognitive map of Yann at the forth stage of the Project of Leadership–Followership.

3.4.3 How much knowledge sharing is enough for an IDCT

How the shared knowledge develops can be revealed by a summary of the collaborative process of the 'Leadership–Followership' group. By opening multiple possibilities before meetings they quickly integrated their concepts and converged their ideas into proper structures of shared knowledge. Two pairs of isolated notions between Marilyn the social psychologist and Weiss the computer scientists, and one structure of notions each between Yann the physicist and respective Marilyn and Weiss emerged from the discussion. By moving forward, all three of them went into details of their own expertise, as Marilyn into psychological experiments, Weiss into computer simulation model and Yann into physics parameters. However, cognitive maps of Marilyn and Weiss (Figure 3.9 and 3.10) show that neither of them had taken Yann's parameters into consideration. Two versions of explanation on this phenomenon are provided by Yann himself and Marilyn. The former thought it was because his work went more into details than the other two collaborators; but the latter claimed that it was the group's choice. Consequently, there was only one pair of isolated node with no shared knowledge structure between Yann and his two collaborators. Yet connections between Marilyn and Weiss grew stronger. At the last stage, this problem had not been fixed and even became worth because of an unpredictable communication problem. The cleavage between Yann and his two collaborators eventually led to his leaving of the project.

With the help of a series of cognitive maps collected over a long period, we are able to clearly illustrate how the process of knowledge sharing and collaboration develop over the time. Now we come to the question of how much knowledge sharing is enough for an IDCT. In the previous publication (Dai and Boos, 2017), we examined the first stage of the whole process. However we did not really answer the question because we did not prove whether it is possible to build the IDCT with less sharing of knowledge as they have claimed. Yet, it is still fair to believe that we figured out that the degree of knowledge sharing is strong enough to maintain an IDCT.

For the technical collaborative pattern, we claim that the least degree of knowledge sharing between collaborators is an isolated notion. It is fair to claim that this is the already least condition for all conditions of knowledge sharing. So the only problem lies on whether a structure of shared knowledge is of least need for building IDCT in the theory-method pattern. The table 3.1 depicts how much knowledge each pair of collaborators share at each stage. What we can clearly see is that when the shared structure of notions is not fulfilled for theory-method collaborative pattern, one pair of isolated notions is not enough for maintaining the collaboration because later on the physicist left. Thus at least in the case of 'CSP', it has been confirmed that what we have claimed cannot be disapproved.

Table 3.1 The shared knowledge between each pair of the three collaborations at all stages

	Psycologist & Computer scientist	Psychologist & Physicist	Physicist & Computer scientist
Least knowledge sharing for pattern	Technical IDC pattern: a pair of isolated nodes	Theory-method IDC pattern: one structure	Theory-method IDC pattern: one structure
Point of observation: (Oct, 2013)	One structure, one pair of isolated nodes	None	One structure, one pair of isolated nodes
Point of observation: (Nov, 2013)	Two pairs of isolated nodes	One structure, two pairs of isolated nodes	One structure, two pairs of isolated nodes
Point of observation: (Nov, 2013)	One structure, one pair of isolated nodes	One pair of isolated nodes	One pair of isolated nodes
Point of observation: (Dec, 2013)	One structure, one pair of isolated nodes	None	None
Result: Sep, 2015	Co-publishment	Discontinued	Discontinued

3.5 Discussion

This chapter identifies two integral parts that are important in the formation of shared knowledge as boundary objects and illustrates the instability of these shared knowledge by interpreting the detailed process of the development of an IDC project. In doing so, this chapter further confirmed the least degree of shared knowledge for establishing IDCs. Boundary objects have been found changing over the procedure of an interdisciplinary collaborative product. And this change of boundary objects may strengthen, weaken, divide or even ruin the project team.

The two processes of forming up boundary objects are necessary no matter how complicated the processes of establishing an IDCT. They are 1) the process of contextualisation, for establishing a basic agreement on the backgrounds and the nature of certain concrete disciplinary concepts and 2) the process of integration of these concepts, for mutually matching up the needs and offers of each part of the collaborator. Besides, the first process has been found as the premise of the second one. Apparently, they are not newly found as they depict a similar yet much clearer picture compared with the IVM project in Wesselink's case study (2009). She did not realise that the process of contextualisation had been reached in the first phase of the project by identifying a 'wish list' of all kinds of land use (agriculture, housing, industry, recreation, ecology and river management). Integration of knowledge was then went through right after their had characterised all of these information into eight sections of the Meuse valley, based on which they negotiate and fix the shared definition of 'landscape quality' by including perspectives of both economic optimisation and subjective enjoyment.

In this vein, this chapter confirms with Wesselink's work. The two processes mentioned in this chapter emphasises the two crucial points for knowledge sharing that she mentioned yet never pointed out. Compared to other frameworks or designed protocols for forming up an IDCT, these two processes provide more concrete and clearer goals for IDCT formation thus play a role of shinning lighthouses for 'knowledge integration' and 'global question identification' (Klein, 2005: 43). In a broader sense, this study revealing rich details happening in the running of an IDCT is important as recorded stories being learned and lessons being studied.

What is new for prior studies on IDCs lies on the instability of shared knowledge because it happens even on well-established boundary objects. This property has not been discussed partially because the boundary object defined here is not a physical object, like what Star and Griesemer (1989) has encountered. Collins and his colleagues (2007) gave such kind of mental boundary object a new name, 'internationale expertise', in order to separate the two forms. But Wesselink (2009) still included both forms under the name of boundary objects. Whatever name it calls, the dynamics of boundary objects matters because it may influence their functions of linking various knowledge systems. In addition, who says physical objects are all stable?

Instability of shared knowledge is associated with multiple interpersonal factors like the willingness to collaborate, trust (Bendix et al. 2017), ability of dealing with conflicts, different research cycle among others. In this particular case, it is the pressure on quick research and publication associated with different levels of research statues that finally triggered the dissolving process of the discussion group. As Weiss's work played a crucial role in the work flow, everyone needed to wait for his progress. This pipeline was thus fragile which implied the potential conflict shown in last meeting. Plus, the various ways of collaboration and distinctive rules of disciplinary community all contribute to different definitions and duration of 'trial time' and 'pilot study'.

‘Publish or perish’, this doctrine remains a dominant research philosophy in German academia and the interdisciplinary collaboration projects understudy is no exception. The key to success in the IDC is about how to do research and collaboration efficiently and effectively. This issue will be further discussed in Chapter Five.

Chapter Four

Interpersonal Mechanics of Knowledge Interaction

Chapter Four deals with interpersonal mechanics of knowledge interaction via investigating how cognitive maps of scientists interdependently change during interpersonal communications in the context of interdisciplinary collaborative teams (IDCTs). These communications have been observed through one year's fieldwork on three quadruple-people IDCTs consisting of not only senior researchers but also junior researchers, which will be introduced in details in section one. The section two illustrates specific empirical findings of how people divide their labour in IDCTs. In doing so, this section teases out which group of scientists conducts what type of sub-task of the project separately. The third section sheds light on work interdependence in terms of task synergy and knowledge connections, followed by theoretical analyses of three interactive modes. The interactive modes will be given in the last section.

4.1 Research Questions

4.1.1 Sub-questions

Interpersonal mechanics of knowledge interactions in IDCT is examined by the following sub-questions: first, how people divide the whole interdisciplinary project into sub-tasks and distribute them to each team member (section 4.2.1)? Being assigned a certain component of the project, what kind of roles does each individual scientist from specific disciplinary and hierarchical positions play (section 4.2.2)? Second, how do people integrate their divided parts of the project together in order to run a smooth and solid work flow, namely to work interdependently? And how do hierarchy and disciplines as two factors influence this work interdependence (section 4.3)? Third, is there any mode of interactions among people in IDCTs that is shared by all selected cases as the interpersonal mechanics of knowledge interactions (section 4.4)?

4.1.2 Research interdependence

In order to further conceptualise the terms of research interdependence and the division of labour, it is important to pay close attention to two aspects under the name of 'dependence'/ 'interdependence' discussed in the following prior studies.

The first one relates to the interconnectedness of research content among researchers. Whitley (2000) claimed that due to the fact that the academic field was a platform on which scholars earn and consume academic reputations for title promotions, people in the same academic communities (normally mono-disciplinary based) were mutually dependent on each other. His concept, functional dependence, refers to the extent to which people need to employ published results of each other and follow certain specialists. However, it ends up with bibliographic network analyses on citation and co-publication relationships, which are the results of science works, thus is still not able to present daily work process. After all, a tremendous amount of daily interpersonal communications on detailed knowledge exchange and integration have already taken place before the birth of publishable articles (has been discussed in 1.5.2). They do matter because during the communicative process, what a speaker means sometimes can be quite different from what the listener understands (Burkart, 2002). People from various disciplines may use the same pool of scientific vocabulary, but terms out of which have different meanings in their respective disciplinary contexts (Jakobsen et al., 2004; Dai and Boos, 2017). In fact, it is reported that many IDCs failed because of misunderstandings on scientific concepts, methods, research objects and so on (Tress et al., 2007).

Thus the content interdependence discussed in this chapter happens between single researchers rather than within an academic community. Thus the content interdependence in this chapter is defined as the strength of shared knowledge between two running knowledge systems. The knowledge is shared when scientists concretely share the same meaning of specific scientific notions. In this vein, the content interdependence depicts the extent of knowledge integration. It cannot be captured in the final products of the IDCs, such as the citations nor co-publications, but in the process of daily interdisciplinary knowledge co-production.

Second, high degree of content interdependence ensures people in IDCTs understand each other, yet is not able to secure the synergy of each components of collaborative tasks, without which the collaboration will be conducted disorderly and inefficiently. The concept of task interdependence between activities describes ways of organising interrelated teamwork flows; and there are four different 'task interdependences' that are summarised from previous studies (Thompson, 1967; Puranam et al., 2012; Cummings and Kiesler, 2014; Häussler and Sauermann, 2016). Tasks are (1) pooled, when components of works are done independently followed by being simply pooled together as a collected output; (2) sequential, as the output of one work plays a role as the input of another; (3) reciprocal, in which work flows of researchers run in 'back and forth'; and (4) simultaneous, indicating work entities being performed at the same time. These types of task interdependence imply two points about the tasks of a team: the content of the research project consisting of several (sub-) tasks and the ways to arrange these (sub-) tasks. Designs on these task flows have been claimed as a number of tools and protocols by studies on interdisciplinary collaborations (Klein, 1990; Clark and Brennan, 1991; Selin and Chavez, 1995; Clark, 1996; Jakobsen et al., 2004; Bergmann et al., 2005; MacMynowski, 2007; Godemann, 2008). That said, not many empirical researches have focused on task distribution and coordination that are practising during team-based interdisciplinary knowledge production. Even though some investigations on interdisciplinary workshops (Heemskerk et al., 2003; Wesselink, 2009) have been conducted, there is still very little research that studies teams working daily in laboratories and offices (exception includes DuRussel and Derry, 2005), one of the most common ways of interdisciplinary scientific knowledge production.

Even though interdependence between tasks has been demonstrated not to be relevant between people who work on these tasks (Puranam et al., 2012), this chapter combines interpersonal content interdependence and (inter-)task interdependence by asking a simple question: during a typical IDC project, who does what in what sequence? Only having understood at first how people divide their labour, namely by what means team members distribute sub-tasks to each individual participant, can we further answer how these sub-tasks are arranged in a work flow, even though they are two sides of one coin. Thus division of labour will be examined before interdependence is further elaborated.

4.1.3 Disciplines and team hierarchy

This chapter considers two interpersonal features: which discipline does a scientist work with and which position is one operating in the hierarchical team, because there are two crucial personal factors having been found potentially being responsible for interpersonal collaboration in IDCTs:

First, disciplines with specific intellectual structures have been found influencing the formation of structures to organise scientists and their research tasks in research teams (Whitley, 1978). In particular, Whitley's case studies show that the differences of research goals and ways of division of subjects in high-energy physics, geological science and medical study centers (a Cancer Center) are associated with different patterns of collaboration inside each discipline. For instance, on the one hand, in the high-energy physics lab, the group of scientists is divided into two groups: one is computer/electronic group and the other is high-energy physics group. Such a division of scientific labour was believed by physicists to follow the nature of physics as a subject of study, which requires an experimental part and theoretical part. Limited efforts was put in solving communicative difficulties between researchers from different groups, as they all believed that they share the common background of knowledge. It truly turned out that they all focused on common research purpose and worked jointly well. On the other hand, the Cancer Center needs to hire researchers from various disciplines who can work together on general medical problems because cancer research itself is related to both basic scientific questions and clinical implements, which are dealt with in different disciplines. However, a puzzle emerges when, for instance, physicists are collaborating with biologists because definitely physics and biology differs in both degree of specificity of scientific objects and of restrictiveness of relevant properties (Whitley, 1978). In other words, it is interesting to reveal whether disciplinary intellectual structure still matter in the context of IDC.

Second, different roles playing in the hierarchical system of an IDCT have also been claimed by the following studies affecting the research interdependence. Partially because of the importance of the research project which makes science as a collective endeavour is rising up (Bendix et al., 2017), a huge amount of scientific works are team dependent and project-based (Uzzi and Spiro, 2005; Wuchty et al., 2007; Milojević, 2007). This kind of IDCTs usually involves a wide range of researchers not only from different disciplines but also with various levels of seniority. For instance, some of the team members, as my informants usually claim, are called as the 'boss' of the others, who work as 'labours'.

Since this research discusses IDCTs in the German context, we take projects funded by the German Research Foundation (Deutsche Forschungsgemeinschaft, DFG in short) as an example. It is clearly requested that the applicants for DFG projects should be 'researchers in Germany, or those working at a German research institution abroad, who have completed their academic training (a doctorate as a rule)'.[12] This implies that doctoral students are not eligible to apply. Yet remuneration of project personnel is divided into three levels: scientific staff, including PIs and doctoral students; student research assistants who are at early stages (such as undergraduate and

[12] See: Guidelines Research Grants Programme, p.2.
http://www.dfg.de/en/research_funding/programmes/individual/research_grants/index.html

graduate students) of their academic studies; and non-scientific staff.[13] If we consider the payment situation and eligibility of being an applicant of the project, it would be proper to roughly characterise IDCT members into only two hierarchical levels: senior researchers and junior researchers, depending on the educational degree and research experience, namely whether he/she is above a PI.

In hierarchical teams, amount of resources, type of tasks, power strength and research abilities are distributed unevenly (Jakobsen and McLaughlin, 2004; Katz and Martin, 1997). As a result, in order to earn identification from the community or necessary resources of conducting academic research, people with a lower power position in this hierarchy have to depend on those with higher power position, willingly or not, by accomplishing tasks assigned by the latter (Peacock, 2016). Latour and Woolar (1979) also found that in scientific laboratories, people in higher positions managed more expertise so that were harder to be replaced than those in lower positions. Coombs (2004) reported that the hierarchical knowledge being held and used by doctors and nurses had been found strongly associated with a hierarchy of roles with asymmetric power positions during the process of decision-making and daily activities in clinics. Thus whether such kind of division of labour also take place in IDCTs is necessary to be discussed.

4.1.4 The fieldwork

The three teams investigated in this chapter were built up by a group of biologists, physicists and statisticians. That is why I name them as the ‘BPS’ group in short. These teams belonged to one of the fourteen grand interdisciplinary projects within the same university under study. They were sponsored by the DFG during my investigation period. Mechanics of germ band extension in the Drosophila embryo was studied by a group of physicists and biologists (Team A); dynamics of Actin Sterm Fibers in various kinds of cells by physicists and statisticians (Team B); and mechanics of mitotic wave within the Drosophila embryonic development by biologists and statisticians (Team C). In this way, distinctiveness of disciplinary contribution can be clearly examined because each pair of combination among biology, physics and statistics have been made up and investigated. All of them were quadruple-people IDCTs, in which, unlike the ‘CSP’ group, there was a pair of senior and junior researchers coming from two different disciplines. In this vein, these cases are representative because they contain at least one researcher on each position of a simplest interdisciplinary hierarchical team. Detailed information on these four teams is shown in Table 4.1.

Information on general content of tasks and division of labour among team members are collected and recorded by methods of semi-structural interviews and participant observation. In more details, I conducted twice day-long participant observation with Leo the biologist in his laboratory and Albert the statistician in his office respectively. Also, I took part in group meetings with researchers from various disciplines, in which they updated working progress they made every week/month, exchange ideas, and set further plans of joint research. Every one to two months, one-hour semi-structural interviews were conducted on all eleven team members of the three IDCTs. Three rounds of such kind of interviews helped to reveal cognitive and organizational developments of these teams. For each team, the whole process of such kind of following up data collection lasted around six months. In addition, at each interview, the informant was asked to give a detailed overview of his/her research and draw them in a cognitive map. Thus

[13] See: Supplementary Guidelines and Instructions, p.5-8. http://www.dfg.de/formulare/1_19/1_19_en.pdf

altogether thirty-four maps were collected, except for senior physicist's and senior statistician's (both in IDCT C) as they did not provide maps during the first interviews.

Table 4.1 Basic conditions of the three IDCTs discussed in Chapter Four

	Research topics	Disciplines involved		Rounds of investiga-tions	Number of interviews	Number of cognitive maps
IDCT A	Mechanics of germ band extension in a drosophila embryo	Bob (SP) Frank (JP)	Chris (SB) David (JB)	3	12	12
IDCT B	Dynamics of Actin Sterm Fibers in different kinds of cells	Grant (SP) Lys (JP)	Will (SS) Alan (JS)	3	12	10
IDCT C	Mechanics of mitotic wave within the drosophila embryonic development	Chris (SB) Leo (JB)	Ling (SS) Albert (JS)	3	12	12

Note: SP=Senior Physicist; JP=Junior Physicist; SB=Senior Biologist; JB=Junior Biologist; SS=Senior Statistician; JS=Junior Statistician. Names of people in this table have been anonymised for privacy protection. The colors of the names present the discipline people belong to: red for physics, yellow for biology and blue for statistics.

Besides these eleven main informants, extra three other scientists were interviewed to cross-confirm the accuracy of the data collected. They are, as has introduced in Chapter One, Jack, Shylock and Jenny.

4.2 The division of labour

This section elaborates who does what part of works in an IDCT by comparing cognitive maps of individual scientists in each IDCT at each stage. Because content of researches may not only depending on specific research topics of the team but also collaborative patterns mentioned in Chapter Three, this section illustrates one example for each pattern.

4.2.1 The technical IDC pattern: IDCT A

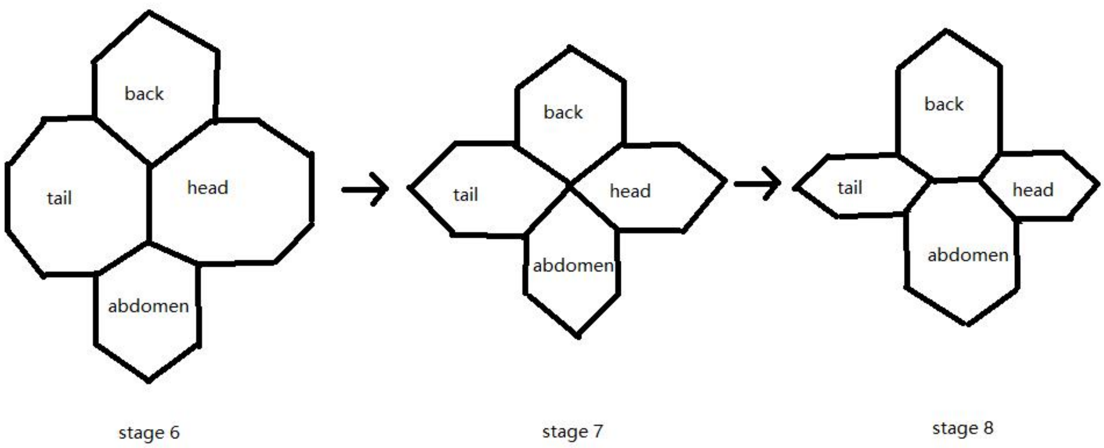

Figure 4.1 An example of the development of a group of four cells during the development stage of 6th-8th of the Drosophila embryo, when the germ band extension of a drosophila embryo is taking place. Each hexagon or octagon represents a cell in the drosophila embryo. The one named 'head' means this cell is locating in the direction of the head of the drosophila. Others are named by the same principle. The size of the cells does not account here in this illustration.

David, who shared the same supervisor and office space with Leo, worked on biological morphological research during the development stage of 6th-8th of the Drosophila embryo. He was in IDCT A with Chris, his senior, Bob, a physicist senior research, and Michael, who was an undergraduate student working for Bob. In this project, David and Chris study how and why a group of four cells in the embryo affect each other in the process of germ band extension (see Figure 4.1).

What had been found is only that the cell of tail and head were stretching during this process; and that the extension of this group of cells went as the back and abdomen cells were getting closer to each other while the head and tail cells were moving far from each other, which made the boundary between the latter vanish and that between the former be established. But much remained unknown including what back and abdomen cells did during this process, what kind of protein were at work, and how much force was needed to make this extension happen.

The work-flow graph of IDCT A and cognitive maps of all its team members vividly show how people divide the whole project into multiple steps and which steps have been assigned to whom as sub-tasks. The work-flow graph was conducted during semi-structural interviews. In more details, each informant of the team had been asked once to describe his/her research procedures, according to which I drew the procedure in the form of work flows. Of course, all such kind of graphs had been checked even corrected by my informants. Thus the work flow graph of the whole team is a summary of all work-flow graphs of team members.

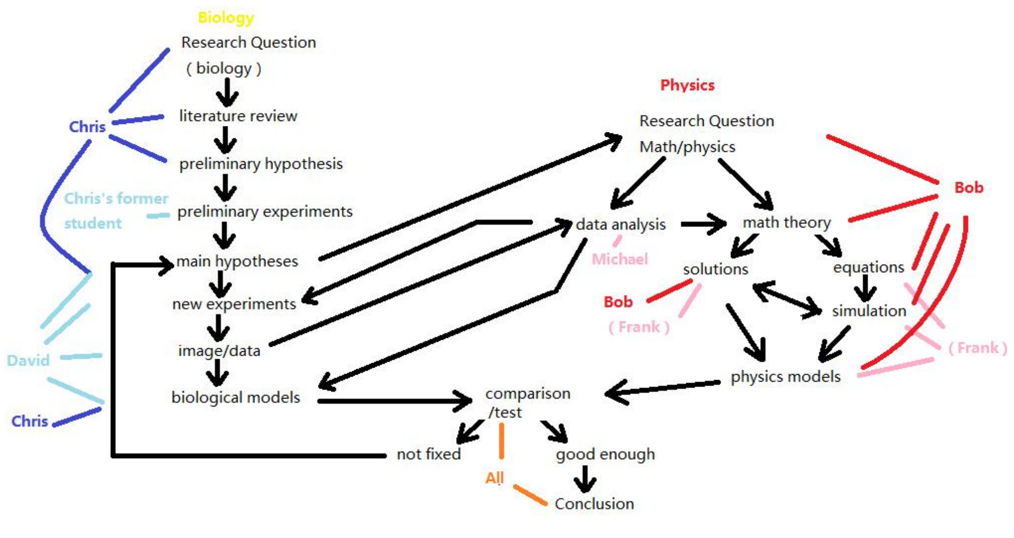

Figure 4.2 The work flow graph that shows the joint research procedure of IDCT A.

Figure 4.2 is displayed as an example of the water-flow graph of the IDCT A. On the left side of the graph visualised Chris' work on *theoretical* part of biology research. He was responsible for setting up question and hypotheses and building theoretic model while his students took charge of hands-on *experimental* part. On the right side, Bob took over the *theoretical* part of physics works, leaving *data analyses* to his student Michael. Frank had weakly involved in this project as he was in his first year of doctoral student and was still learning all kinds of related knowledge. On the bottom of the graph, as the final part of the team research procedure, biological models and physical models conducted by each side finally met and were compared by all participants. As biologists and physicists shared the same theory-initiated research procedure but focused on research problems of two areas, they were in the technical collaborative pattern by the definition of Dai and Boos (2017).

As one of the team leader, Chris described to me how they collaborate with each other:

'*It was in 2010 when we realised that we can go into a more quantitative direction. This is when Bob joined in. And only because he joined, we could make a shift in the direction of the project. At that time there was another student who worked on this. But she graduated in 2013. And she published the first paper, the preliminary study of this project, in 2014, which was not the main paper. The question had been found in this paper. But we did not have the means to do it...Bob collaborated with people in lots of fields...What he did is he applies his knowledge from his field to all the fields [he collaborates with]...which are biologically completely different...but the math behind these goes similar approach...so we provide a nice opportunity for him to move into this direction. Not only to contribute to our project but also for himself to establish a new field of research…*

In this case, it is a simple analysis of some data, like time series, concentration...Bob is an expert on fluctuation analysis, which is an established procedure for them [physicists]. But we [biologists] couldn't do it. So they did it for us...they did image analyses and statistical analyses. They also do modeling. We record cells, and they automatically find the outline of the cells. It is called segmentation. So we know how the cells change over time...Then we look for specific cells who change their neighbors...then we look for correlations, for example, area changes correlated with length changes...then in the end, to Bob who is a theoretician, what they do is that they want to do a mathematical model of this process. What they do is the stochastic processes. Then we want to fit them [models and results from biological experiments] to each other…

The coordination of cells is needed in the T1 process neighbor exchange, which is the cellular bases of the germ band extension. This is the biological process. And the coordination of cells is found by statistical analysis.'

As Chris had introduced, it was David who conducted experiments in this project. Michael and the physics postdoc before him, who was Watson, took charge of the main part of data analysis. Chris himself only thought about general ideas on the big picture of his field and built up biological theories about germ band extension. Even though he was also involved in specific experiments by supervising David when the latter meets technical problems, Chris did not really take part in the practical work of running experiments. These technical problems include situations when David does not know what kind of technique should be used to solve certain problems, or when he finds the results of experiments do not match what is hypothesised and he can not find out why.

Cognitive maps of participants of this project tell in further details how each participant considered this division of labour, namely who was taking charge of which sub-tasks and how these sub-tasks are interrelated. Figure 4.3 illustrates the map of Chris, which presents that Chris's goal of running this IDC was to understand 'coordination of cells', a topic that was designed by both senior researchers. Moreover, Chris tried to build models on the 'germband extension biological process' and his physicist collaborator, Bob, worked on 'vertex model'. In comparison, the phenomena of ‘neighbor exchange’ in T1 process, ‘area changes’ studied by ‘image analysis’ and the experiment on ‘Ca uncaging lase cuts microscopy’ were the works of junior researchers.

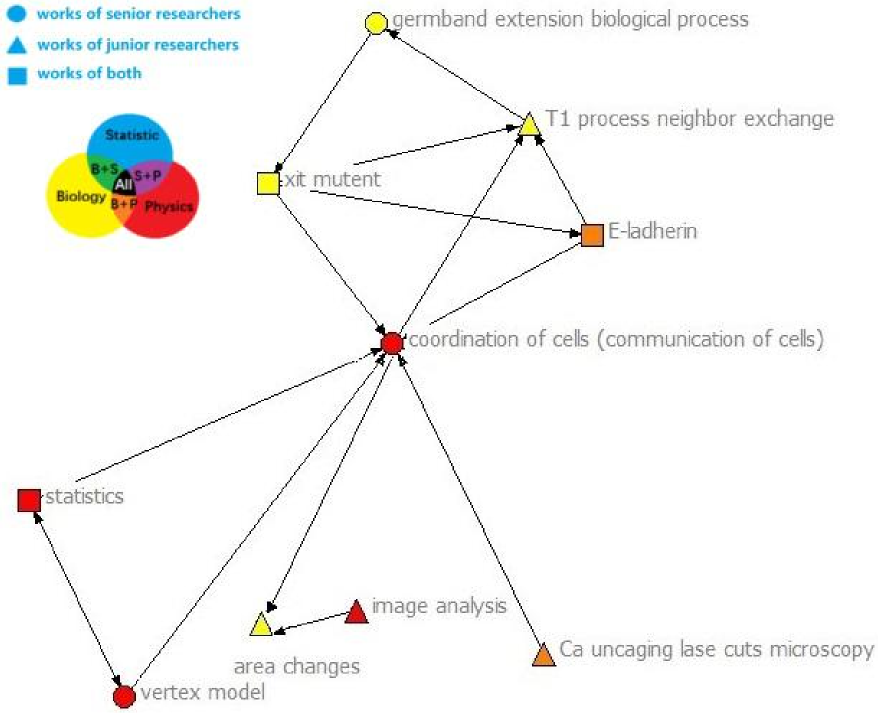

Figure 4.3 (Also **Figure** 2.2) Cognitive map of Chris (IDCT A) at the first stage.

Nodes colored in yellow means works done by only biologists, in red only by physicists, in blue only by statisticians. While the node in orange presents that this work is done by a collaboration of both biologist and physicist, in purple by a collaboration of physicist and statistician, in green by statistician and biologist, in black by all. Node in the shape of circle illustrate that this work is done by only professor(s), in triangle is the work of only student(s). While nodes in square mean they are done by both.

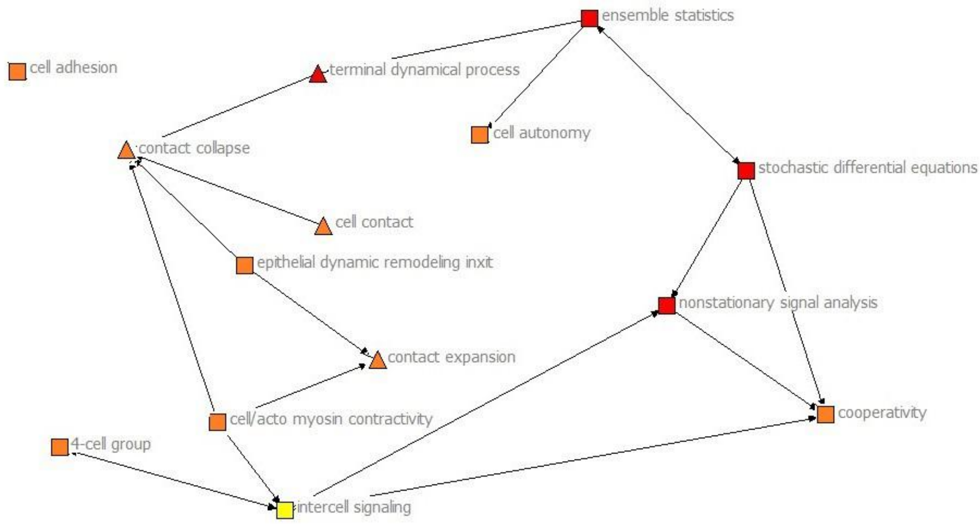

Figure 4.4 Cognitive map of Bob at the first stage. Shape and color principles are the same as in Figure 4.3.

Figure 4.4 shows how Bob thought of the project at the first stage of my investigation. He apparently agreed with Chris to take ‘cooperativity’ as the main goal of their collaboration. But it seems like in Bob’s mind, juniors were also taking part in this notion because all of their works were under the umbrella of this general research topic. What Bob had emphasised on the left part of his map was the specific sub-topics that junior researchers put endeavour: ‘terminal dynamics process’, ‘contact collapse’, ‘cell contact’ and ‘contact expansion’, which covered all kinds of conditions about the ‘cooperativity’ of ‘4-cells group’.

Figure 4.5 shows the cognitive map of David, and Figure 4.6 the map of Michael. Compared to their respective seniors, each of them focuses on more technical details and pays less attention on general ideas of the whole project. For instance, David sets germ bend extension in drosophila embryo development as a common ground of the whole group. What he is taking care of at this stage is just to mark up the target cells and take live images by microscope. Even Michael provided richer information for this process as he gives the name of ‘GFP’ (short for Green fluorescent protein), the protein to mark those cells. Then the images are given to Michael’s hand, who segments the images and conducts a set of statistical analyses on them. Michael lists every detail of these analyses in Figure 4.6, which are works mostly done by himself. Besides, it is necessary to be noted that both of these two junior researchers draw a map as a circle research procedure, which means that the juniors consider their project as cycling experiment-data analyses works.

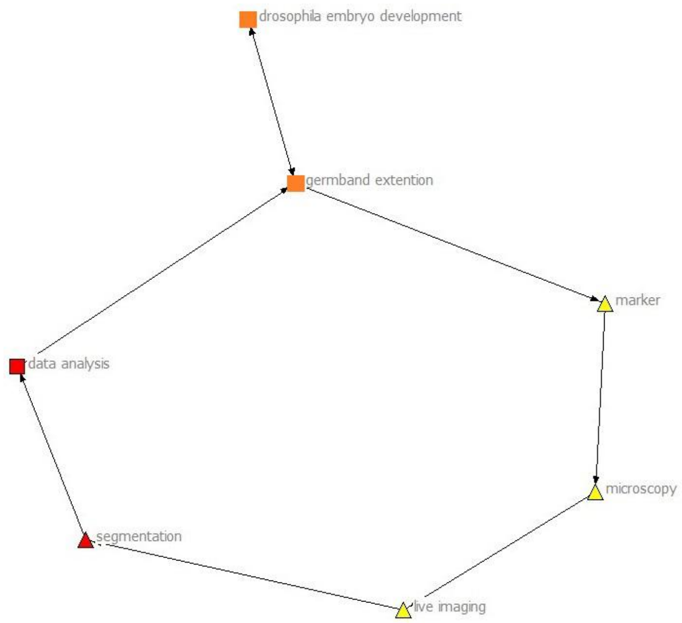

Figure 4.5 Cognitive map of David at the first stage. Shape and color principles are the same as in Figure 4.3

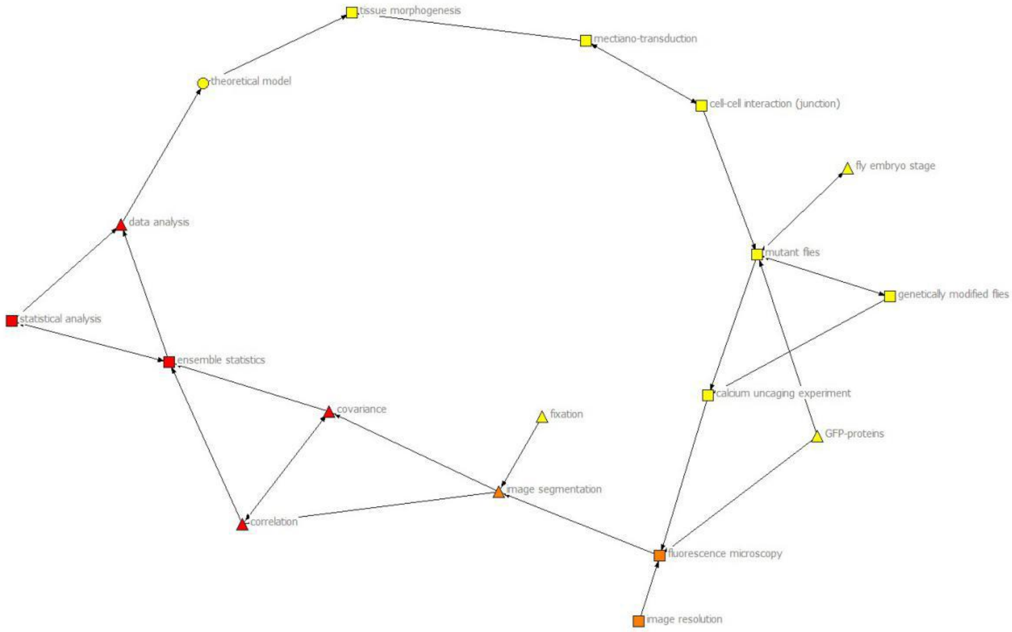

Figure 4.6 Cognitive map of Michael at the first stage. Note: Shape and color principles are the same as in Figure 4.3.

This comparison of cognitive maps demonstrates a two level structure of collaboration among team members in IDCT A: the cognitive division of scientific labour goes as junior researchers are working on the technical level in terms of data analyses and running experiments, while senior researchers set the general ideas of the project. In this vein, the latter helms the direction of the whole project, and the former explores potential possibilities, put ideas into practical research and test hypotheses.

4.2.2 Theory-method IDC pattern: the case of IDCT C

As biologists and statisticians differed in their research procedures but focused on the common research problem, they were in the theory-method collaborative pattern by the definition of Dai and Boos (2017). Even though in a different collaborative pattern, scientists in IDCT C divide their labour in a similar way as in IDCT A. Illustrated on the left side of the work flow graph of IDCT C (Figure 4.7), biology research procedure is divided by Chris and Leo: the former takes care of general and theoretical issues and the latter conduct experiment and analyse the data. On the right side, it seems that Ling as a senior statistician devotes himself not only to designing algorithms and building models, but also to part of data analyses. The junior statistician, Ling's only student, Albert, works on also algorithms and data analysis. Different from the situation of IDCT A, the comparison between biological models and statistics models is conducted by merely senior researchers in the IDCT C.

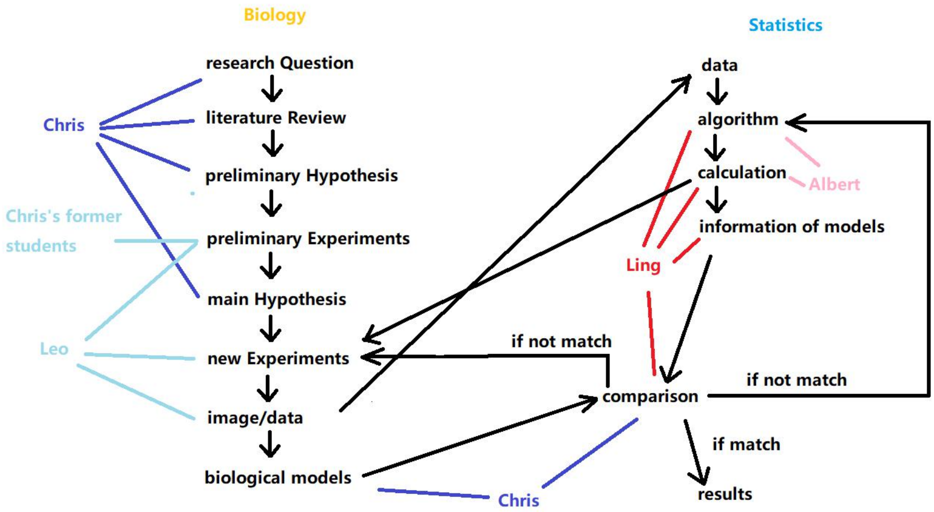

Figure 4.7 The work flow graph that shows the joint research procedure of Leo's project.

On the individual level, Figure 4.8 shows the cognitive map of Chris and Figure 4.9 of his statistician collaborator Ling. Chris put the notion 'nuclear array arrangement of nuclei' in the centre of his map as the main research topic of this project, which belonged to the work of both him and Leo. Analyses on 'collective behavior' and 'self-organization' were believed done by Ling, his statistician senior researchers. This can be confirmed in Figure 4.9 as Ling claimed that 'order parameter analysis', 'fluid dynamics' and 'physics concepts of thermodynamics' were all his works. In Figure 4.8, 'flow' was the notion junior researchers were working on, which can be understood as in Figure 4.9 'trajectory finding' and 'trajectory analysis' on 'stochastic processes' of some stuff in 'cell biology' (which in fact meant 'nuclear array arrangement of nuclei').

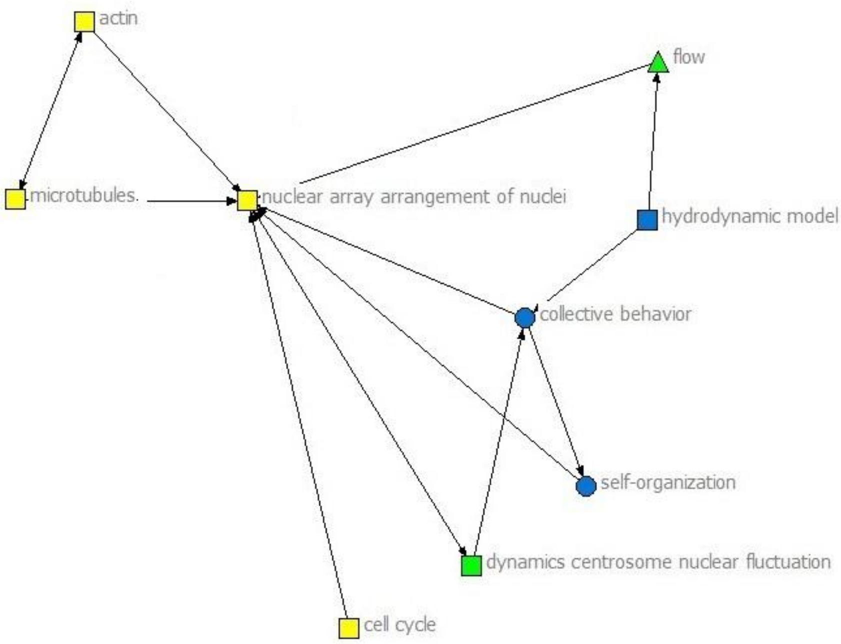

Figure 4.8 Cognitive map of Chris (IDCT C) at the first stage. Shape and color principles are the same as in Figure 4.3.

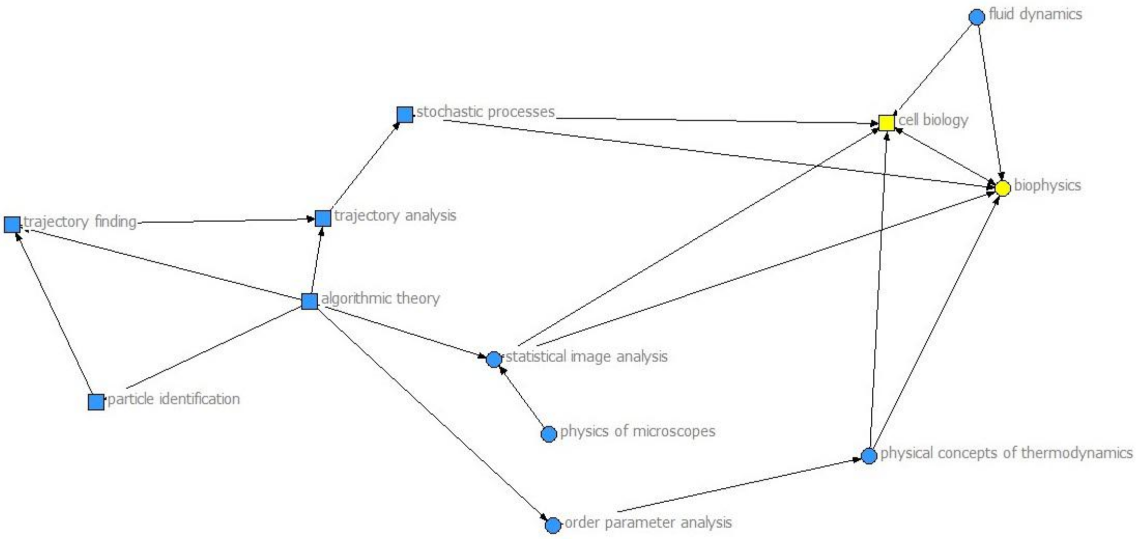

Figure 4.9 Cognitive map of Ling at the first stage. Shape and color principles are the same as in Figure 4.3.

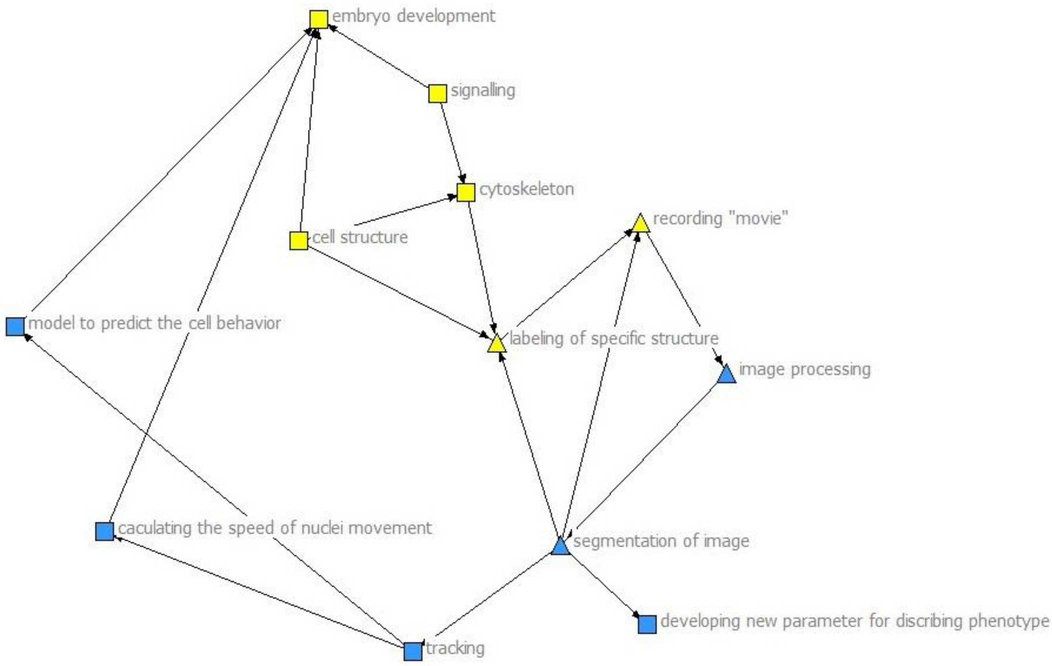

Figure 4.10 Cognitive map of Leo at the first stage. Shape and color principles are the same as in Figure 4.3.

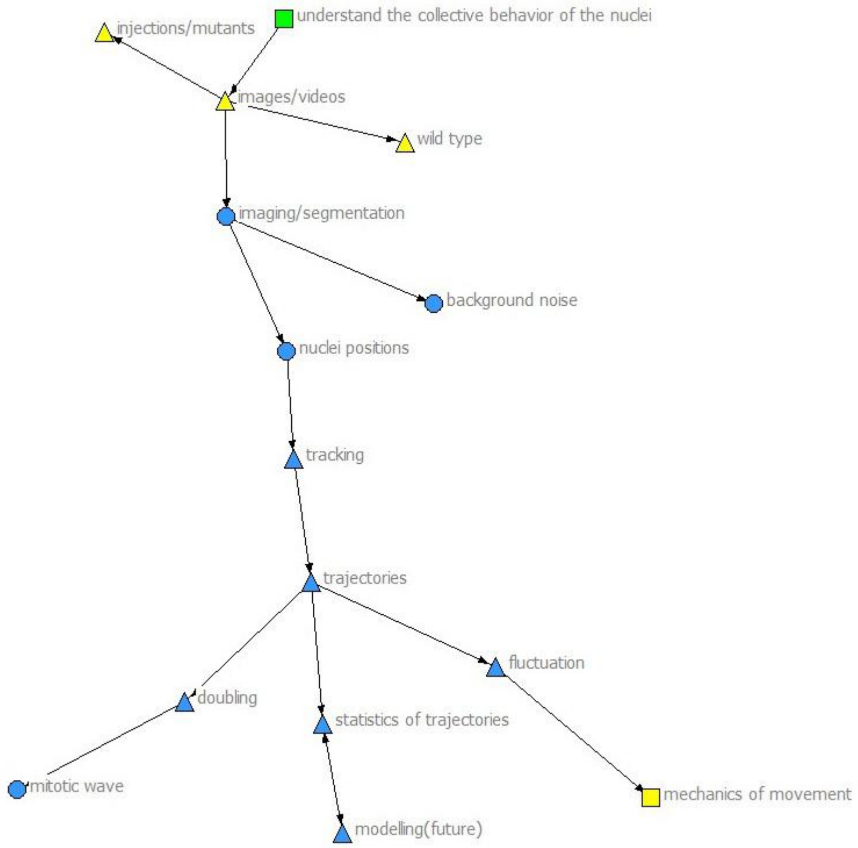

Figure 4.11 Cognitive map of Albert at the first stage. Shape and color principles are the same as in Figure 4.3.

Even though both Chris and Ling thought that notions of the research topic and general ideas of the project were also involved by junior researchers, the seniors claimed that it was so because juniors were working on part of the components of the project, which would help to understand the whole picture. Eventually these components were puzzled up by seniors because juniors were lacking of the ability of mastering all sub-areas related to the project nor of integrating them into one clear argument. Even Leo and Ling agreed on this point.

But juniors indeed listed exactly what notions they were working with, which could be seldom observed in the seniors' maps. It implies that they were focusing on more details of practical experiments and data analyses than the seniors. For instance, Leo's map (Figure 4.10) illustrated four junior-occupied notions, which were all about taking and analysing the movie of the cells. Albert (in Figure 4.11) gave three directions of dealing with 'trajectories' besides merely finding/tracking and analysing them: statistics on them would lead to the model building, the doubling of them were used to simulate 'mitotic waves' and studying 'fluctuation' of them helped understand 'mechanics of movement'.

It confirms that in IDCT C in the theory-method pattern, there are also two levels of collaboration: junior researchers were focusing on more detailed and technical works in order to support senior researchers generating understandings on core and big pictures of the grand research topic.

4.2.3 Role of hierarchical positions

It seems that a clear division of labour in the 'BPS' group have been found according to the position in the hierarchical team, namely being a senior researcher or a junior, no matter in what collaborative pattern nor in which discipline. This paragraph further elaborates roles played by the seniors and juniors as a summary of the whole section.

Senior researchers: theory builders

Senior researchers are theory builders, even though theoretical goals of various disciplines are different.

As cited in 4.2.1 Chris mentioned that Bob was able to conduct fluctuation analyses, image analyses and statistical analyses for biologists, while Bob himself also got a good chance to develop his own theories in physics. This is quite a neutral exchange as both sides benefit from this joint project. This is also echoed by Figure 4.2, which shows that both of their research procedures start from establishing questions, followed by potential theories and hypotheses. It partially because of physicists' trying to defend their subjectivity in the joint project. Bob told me, '*we are not slaves of biologists*', which means that physicists should not play a role of only data analyser. On the contrary, he thought physicists need to employ these data, which come from living animals as an distinctive experimental environment setting compared with in physics laboratories, to develop new physics theories. He emphasised to me that '*our goals are different...In biology, what is the picture for biologists, what satisfied their curiosities are different from in physics.*' In more detail, biologists take care of '*what*' questions like what proteins are stretching nucleus in certain period of embryo development. But physicists ask the '*why*' questions. For instance, why this protein has the stretching function? Further, how much Newton of force does the protein need to fulfill this function of stretching? By answering these questions, the mechanics of the movement is able to be described.

Compared to physicists, the goal of statisticians being participant in IDC projects was to develop new algorithms, which could be packed into new software. Ling has been a good example. Another statistician Will also said: '*there are rumors that statistics has fallen to be an instrumental discipline, analyzing data for other disciplines. But I also build the theoretical model [with data from other disciplines]. And now I have developed it much.*' He even asked his biophysicist collaborator to conduct extra experiments in the need of testing his new mathematical models, though in some cases the latter told him that experiments required by him were impossible because of technical problems. He figured it out as a severe communicative problem and told me twice during my interviews.

In sum, no matter in which discipline, setting an algorithm or a theoretical argument as a goal, professors and PIs in IDCTs like the 'BPS' group are theory builders. Moreover, seniors establish IDCTs based on their strategic arrangement of developing theoretical ideas. In particular, they need general overview of the whole research field and keen judgement on what technology and new theory points are valuable and doable in his/her own laboratory, and how to get access to resources potentially required by experiments in his/her laboratory. In the 'BPS' group, by demands of data analyses and model building, biologists require helps from statisticians and physicists. But the latter does not only finish what are asked for. Rather, they make full use of this chance by translating biological questions into physics or mathematical language so that turn it into a valuable and creative research question in their own field. Sometimes they also 'counterattack' by asking for more experimental data. In this way, both sides hold the direction of the whole project together, setting hypotheses and technical requirements, with which they deal with basic theoretical deduction and reasoning works.

Junior researchers: data analyser and experimenter

Discussions among juniors are more technical than among the seniors. Indeed role of the post-doc and students of all levels are the data analyser and experimenter, who provide raw data and analyse data by transforming them into curves and tables. These data are supposed to be shown to their senior collaborators for whom to construct models and hypotheses.

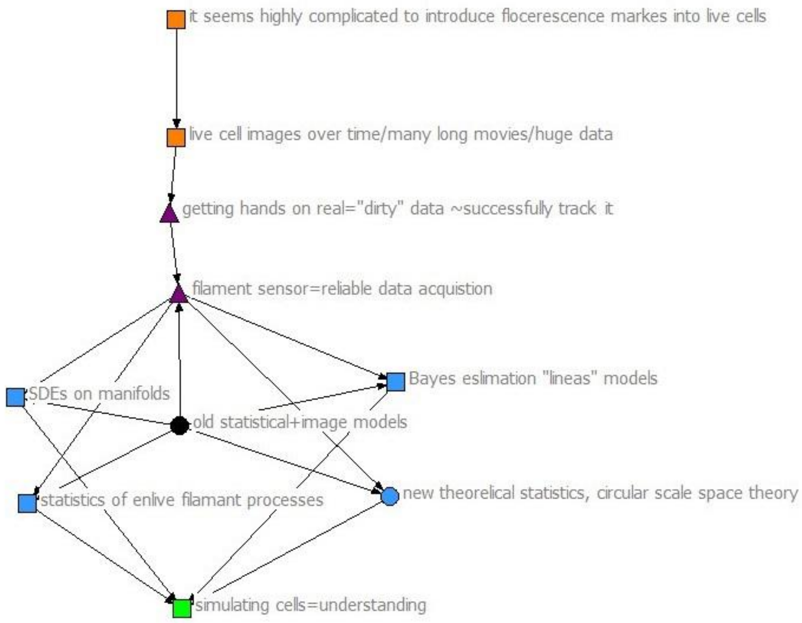

Figure 4.12 Cognitive map of Will at his first stage. Shape and color principles are the same as in Figure 4.3.

Metaphorically speaking, the juniors are infrastructural engines of the whole IDCTs like the 'BPS'. A more interesting metaphor made by Will was that his post Doc, Alan, was playing a role of data cleaner: '*the raw and real data is dirty. There are so many noises so that you can not see the true laws behind...So Alan gets his hands dirty in order to clean the real live cell imaging data into high quality data, which can be detected by our filament sensor.*' This is also illustrated in Will's cognitive map in Figure 4.12, which clearly shows both the roles of data analyser/cleaner played by Alan and theory builder played by Will himself, and how Alan's cleaning work support Will's model building by providing the latter data without much chaos, labeled by filament sensor.

Then what a data analyser or an experimenter does in daily academic daily lives? I have followed respect Leo and Albert, each for the whole day, and taken part in their group meetings in order to understand how do their daily academic lives goes on. Indeed both of them were very busy working on their technical issues. Leo was almost running among his office, microscope room and 'fly room', in which millions of Drosophila were kept inside thousands of glass bottles, namely so called cages or plates in biologist's language. His work can be summarised as a loop of feeding flies in the 'fly room', then making samples of drosophila of files and observe, or more precisely recording images and videos by microscopy downstairs, finally transforming these images and videos by the need of Albert, who would analyse them further. These works require not only clear minds of operating steps, deep understanding and experienced managing to hundreds of technical detailed skills, but also strong physical strength. By taking rests in his office, he read references of the latest journals. A vignette of the first half-hour work of him on a Friday goes as follows:

Figure 4.13 A glance at the fly room. There are tens to hundreds of fruit flies in each cylindrical glass cage, which is displayed in marked plastic boxes. Photo provided by my informant Peter, Dec, 2017.

8:30 I enter the office. It is a wide corridor rather than a small room that links two labs. In this office, papers, screens, electronic wirelines, and all kinds of tips are characterised on two long desks, beside which six chairs, three in each side, are distributed in two lines.

8:48 Leo enters the office with David (they live in the same building), turns on the PC, and puts off his jacket, hangs it into his locker.

8:51 All settled down well, Leo enters the 'fly room'. Here the yeast, which is most favoured food by Drosophila, is smeared on caps of the cages. Some cages are small, some are large for feeding more flies. There are hundreds of thousands of cages, in which millions of flies are living their lives of eating, growing, mating and spawning, in this fly room.

Leo smears yeast on a set of grouped and marked caps. Then within two seconds, he picks up one cage of Drosophila, knocks them down to the bottom of the cage, and changes a new plate on it. Finally, he carefully marks on the cage the time, '8:51'. Having changed plates on two cages, he puts them in the refrigerator on 20℃. David is observing his samples by microscope on the other side of the same room.

8:55 '*We only need two cages of Drosophila.*' Leo explains to me on the way we go back to his office, '*today, before Albert comes to our meeting at 10 o'clock, I need to process some movies of developing process of embryos of Drosophila that I made before. I will send Albert these movies and ask him to analyse them. So, I need to format them in a way easier for Albert to conduct his analysis. After we finish the meeting, I will do some experiments (which are related to Albert's analyses).*'

8:56 Leo sits down before the most powerful computer in his office, an iMac, and starts to download his data from the server. '*Because we cannot install virus protecting software in the PC at the microscope room, we save our data on the server. Yesterday the server almost crashed down, which really frightened me. After I had copied my data from the server to my hard disk, the server recovered…*'

8:58 '*Firstly, I need to transform the movies from .czi, which can only be recognised by special software, to .tiff. However, each movie in .tiff is quite large. You see, this one is 3.77 GB. So I need to compress it into 72.5 MB, which, for Albert, would be much easier to be analysed…I also need to separate movies into several single files by developmental cycle of Drosophila. For example, this file is the 12th cycle, and this is the 13th. So Albert will clearly know what he is working on. See? We are trying our best to make the collaborators' works easier, that is, we make our work simple and understandable even to those who have limited biology background…Last year, when we had IC with a physics lab, we did not separate movies by cycles and they did not have relevant biological knowledge. As a result, they had spent a lot of time to solve some problems that we could finish in seconds. This experience inspired me that I should solve all problems that I can before I provide my data to collaborators…As well, I have designed a table for all information about the movies…*'

9:02 Leo firstly compresses a movie by a special software. Then he opens the movie and turns it around until the embryos of Drosophila is displayed horizontally. Finally he adjusts the frame in order to fill only the embryo in the window. '*There are four movies in which pictures are taken every five seconds. Nine for every two seconds, and six movies for injected embryos. We need to format them all. This is boring but this is exactly what we will do before Albert comes.'* He explained.

Conducting experimental data, Leo had been working the whole day and every work day like this.

In comparison, Albert stayed all day long in his big, bright and tidy office, except when he had cups of coffee and seminars. Normally, with him and his colleague sitting still before computers, only cars rushing through the road nearby could be heard. However, being asked whether they would like to be followed the whole work day and be observed, both surprisingly said the same sentence: '*Are you sure? It is very boring after all*.'

The data cleaning and analysing process seems almost boring as it may seem mechanical and repetitive for one, who is skilled and familiar with the experiment procedure. Albert just sit before his computer. Beside his mouse laid three thick volumes of references and a big bottle of water (just as Figure 4.8 shows). The work of him started by clicking videos conducted by Leo, followed by running his segmentation program on those videos. Then he turned on new videos which was processed by the program, checking whether all little shining points, which were nuclei of fruit flies, had been marked by red markers. In some of the videos, nearly all points were successfully marked, while in some others, points near the edge were not detected by the program. There were always one or two videos that made Albert annoyed as all the points were not recognised by segmentation program at all. Then Albert compared successfully processed videos to those unsuccessful in order to find out parameters of videos that were able to distinguish the latter from the former. Afterwards, he opened the source code of the program, trying to figure out why these parameters happened to effect detecting results. Sometime he turned to the volumes of references and checked whether he was deploying the right equation or whether he had missed any preconditions. Then he changed several lines or parameters of the program codes, followed by running it again to those videos. His work went in this loop, until he got satisfied results.

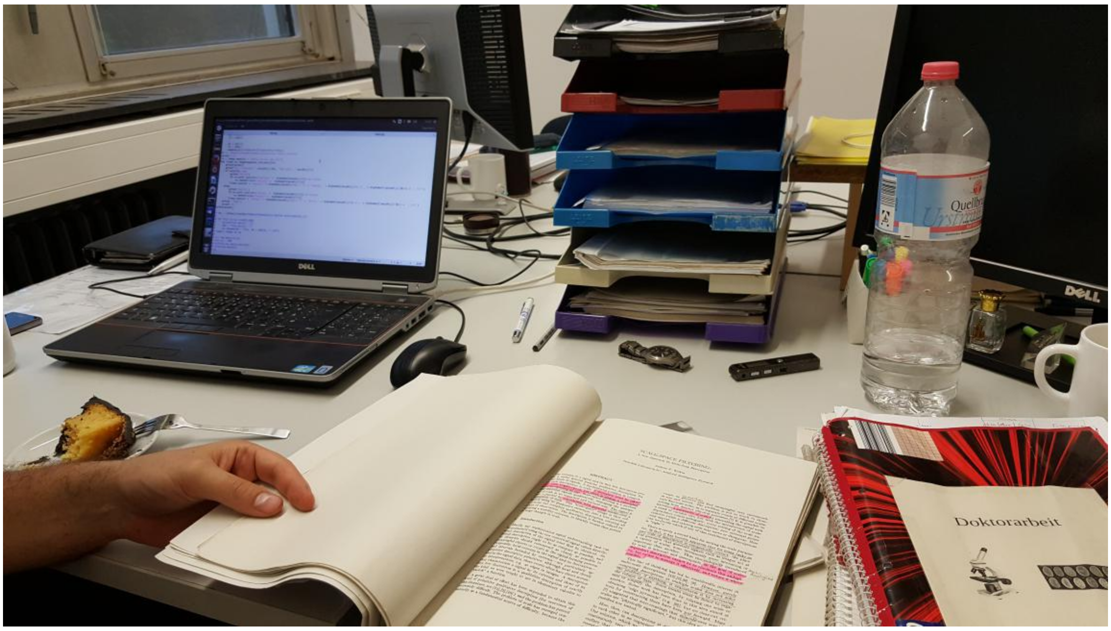

Figure 4.14 Albert's desk in his office. Photographed by Lianghao Dai, Nov, 2016.

The above ethnographic account has clearly illustrated how juniors as data analysers and experimenters were immersed in the sea of details. In the whole day they kept their eyes on every tiny step of experiment and program-coding. Any negligence on one might cause mistakes of the results. Even though, they still occasionally encountered many, which required them to go back and forth into every coding line, physics parameter, chemical reaction, and biological observation that they had deployed in the experiment process in order to figure out the reasons of those flaws and to fix them. Hard steps of progress were made by several rounds of such kind of flaw testing, and easy steps were just previous hard steps having been gone through. In this vein, unlike theory builders who need visions of the whole research area and inspirations on scientific ideas, data analysers and experimenters need patience, carefulness, skills and rich experience with practical operations. Data processing is the base of the whole project as well as base of doctoral training.

4.3 Interdependence

How scientists of the 'BPS' group integrate their assigned components of the project according to others' progresses, namely interdependently? As introduced in 4.1, we consider how hierarchical positions and disciplines are responsible for content and task interdependence. The section 4.2 emphasised the great influence of the hierarchy to the division of labour. One may also wonder, does not the discipline matter to work interdependence of IDCTs? How does each factor affect each kind of interdependence? We double-cross these two parameters and formulate these four sub-questions:

SQ1: how does hierarchy influence task interdependence?

SQ2: how does discipline influence task interdependence?

SQ3: how does hierarchy influence content interdependence?

SQ4: how does discipline influence content interdependence?

4.3.1 Operationalisation of the interdependence

Defined in 4.1.2, content interdependence refers to the interconnectedness of research content among researchers. The strength of such ongoing, practicing and interpersonal epistemic connections between two scientists can be calculated by the number of notions shared by both of their cognitive maps.

Task interdependence, namely how people's work flow depend on each other, can be represented by synchronization of density trends of their cognitive maps. Density analysis of cognitive maps is employed to illustrate dynamic cognitive trends of each informant. The density of a network is defined as a ratio of the number of edges to the number of possible edges (Scott, 1991); it is a structural parameter revealing the extent to which all concepts, tasks, methods or theories are connected in a knowledge network. Similar to the semantic network (Yu et al., 2016), which is defined very much like the cognitive map but with nodes representing only concepts and links as semantic connections, a cognitive map with higher density means the person who draw this map is focusing on a more specific and complicated task, making his/her ideas more useful than those with lower density of cognitive map. By plotting densities of all stages of each informant, a curve of one's work process with certain extent of focus is shown. In this way, task interdependence can be analysed when such kind of curves of all members of one IDCT, namely density trends, are shown together.

The team, named as IDCT L consisting of Marilyn (senior social psychologist/SPS), Weiss (senior computer scientist/CS) and Yann (senior physicist/PS) working on the 'Leadership–Followership' project of the 'CSP' plus three above-mentioned IDCTs in the 'BPS' group (see Table 4.1) are included in the density analyses. The idea of this comparative study on the first and the other three teams is to test whether the potential modes of research interdependence among junior and senior researchers change with participation/absence of the juniors. Thus IDCT L is considered only in discussions on SQ1 that is related to influences of hierarchy on the synchronization of density trends.

4.3.2 Findings: Stratified interdependence among IDCT members

The analyses claim the following findings. First, Figure 4.15 illustrates how IDCT members' respective understandings on their own project develop interdependently. It can be clearly seen that in each team, on the one hand, nearly all pairs of dark curves, representing trends of densities of cognitive maps of senior researchers, move up and down together. The exception only exists at the first to second stage of the IDCT C, in which senior biologist's concentration of knowledge goes denser and senior statistician's declines slightly. Moreover, even in the IDCT L, a team made of purely senior researchers, this finding still holds true. On the other hand, all pairs of light curves run in an opposite way: when one increases, the other in the same team falls down. These findings imply that senior researchers in an IDCT share synchronic paces of concentration of knowledge; they spend many or few attentions on research projects together. By contrast, juniors are working asynchronously. In addition, it seems like no matter what discipline takes part in, this trend of density, namely task interdependence, keep the same. This difference of synchronization between pairs of seniors and of juniors demonstrates a stratified inter-dependency: inside groups of seniors or of juniors, their work flows highly rely on each other; yet between groups of a seniors and juniors, there is a division of labour.

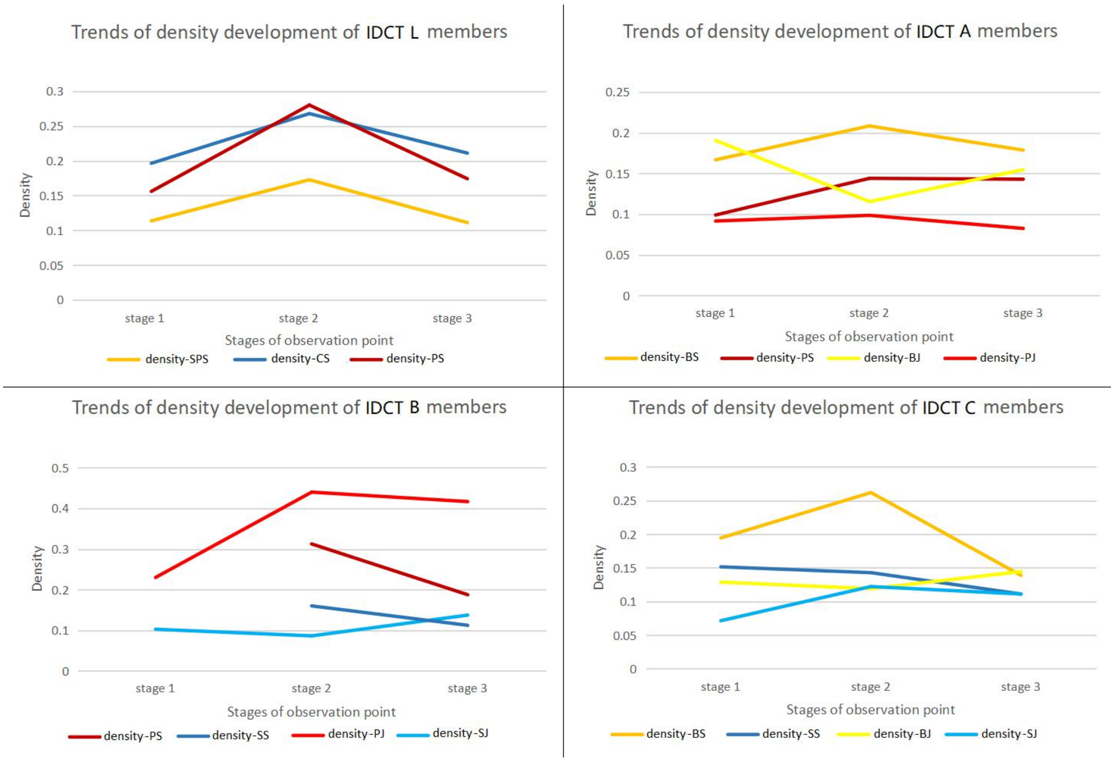

Figure 4.15 Density trends of cognitive maps of all four IDCT members. IDCT=interdisciplinary collaborative team, SPS=social psychology senior researcher, PS=physics senior, CS=computer science senior, PJ=physics junior, BS=biology senior, BJ=biology junior, SS=statistics senior, SJ=statistics junior.

Second, the average degree of content dependence between each pair of interacting informants at each stage of each IDCT has been shown by Table 4.2. As it is reported that '*few communication happens between seniors and juniors who belong to a different discipline*' (Leo, junior biologist in IDCT C), we look at the rest of possible pairs in quadruple-people IDCT A, B and C.

Table 4.2 Average degree of content dependence of research content between each pair of interacting informants of each IDCT (A, B, C).

	AVE-IDCT A	SD-IDCT A	AVE-IDCT B	SD-IDCT B	AVE-IDCT C	SD-IDCT C
S-S	3	1	2	2	2	3
J-J	3.7	0.33	2.7	0.33	2.7	4.33
AVE-Dis-SJ	2.15	0.57	2	0.67	1.85	1.37

Note: Table 4.2 illustrates the number of overlapped notions between two senior researchers (S-S), two juniors (J-J) and the average number of both pairs of a senior and a junior in the same disciplines in an IDCT (AVE-Dis-SJ). AVE-IDCTx means the number in the first column is the average number of all stages of this IDCT. SD-ISCTx is the standard deviation of IDCTx.

As illustrated by the Table 4.2, first, the average number of overlapping nodes between juniors is no less than between seniors, implying that the content dependence of research content between juniors is stronger than between seniors. Secondly, all average numbers of overlapped notions between pairs of researchers in the same disciplines is no stronger than between pairs of interdisciplinary. Thus on the one hand, it can be concluded that the intellectual communications of interdisciplinary teams run mainly between pairs of junior researchers and then of senior researchers. On the other hand, it suggests the missed information that cannot be figured out clearly from Figure 4.15: communications between each pair of senior and junior from the same discipline also play a role in the practice of interdisciplinary researches.

Third, the effect of disciplines on content interdependence can be generated from further analysing number of overlapped notions illustrated in Table 4.2. The sharing of notions between biology and physics in Team A is equal to the number of nodes shared by pairs of both senior physicist and biologist and the juniors, which is 6.7. In the same regard, physicists and statisticians share the number of 4.7 notions, while statisticians and biologists, 4.7. As very few notions are shared by all three disciplines in my cases, it is easy to calculate that physicists require the equal number of shared notions with biologists, which is 11.4, while statisticians need only 9.4 shared notions. Indeed, the informants always complain that '*physicists want to know everything when they try to collaborate with you*' (David, junior biologist in IDCT A), while '*statisticians even do not care what kind of cells you are studying on!*' (Lys, junior physicist in IDCT B)

Fourth, via above analyses it seems that no clue has shown to prove an influential consequence of task interdependence caused by disciplines. If we show the average of density of both senior and junior researchers of the same discipline, we still cannot find out a clear pattern of synergetic correlation relationship between any of curves in Figure 4.15. That said, what the curves do tell is the difference in extent of focus employed by scientists from each discipline. In comparison, biologists try to keep highest connection of research notions in minds during collaborative practice, suggesting that they are dealing with more specific and complicated tasks than other. Statisticians seem like are focusing on more abstract and simplified tasks than people from two other disciplines. Physicists stand in the middle of the two poles. It also indicates that the synchronic development of focus shown in IDCT L due to the senior position in the hierarchy, rather than the relationship between disciplinary intellectual properties.

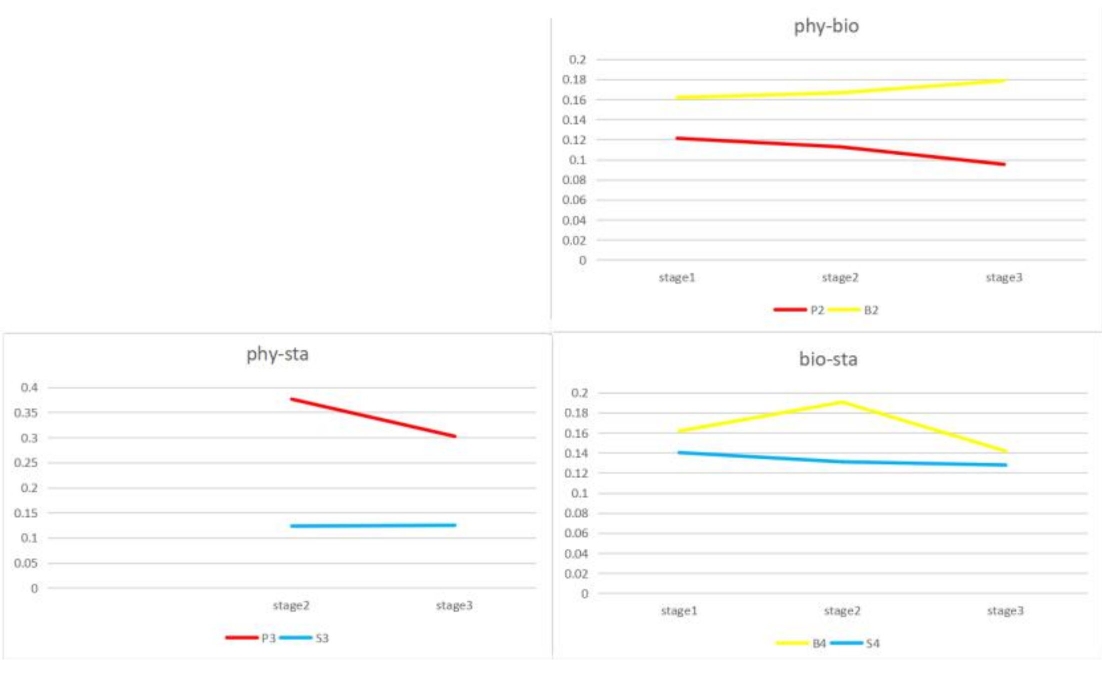

Figure 4.16 Averaged of senior and junior researchers' trends of density of cognitive maps of all four IDCT members in IDCT A, B and C.

In sum, expect to SQ 2, to which the answer is negative, we have found certain phenomena responding to three other sub-questions. In particular, it has been revealed that in each team, junior researchers work asynchronously but with strongest linkage of knowledge system; seniors are working on the same pace with less close overlapped knowledge systems; while groups of a senior and a junior from the same disciplines contribute less yet solid efforts to the projects. In parallel, disciplines affect the extent of not only knowledge sharing in IDCTs, but also the abstraction and complexity of tasks people are dealing with. In other words, disciplinary distinctions of cognitive structures merely affect the extent of content interdependence, and that hierarchical difference of cognitive structures is more crucial than the former in deciding how people organise their interdisciplinary collaborative teams interdependently.

4.4 Interpersonal mechanics of knowledge interactions

The interpersonal mechanics of knowledge interactions in IDCTs in the 'BPS' group is attributed to three modes of interaction between IDCT members. These modes also explain why organisational hierarchy plays such a crucial role in both task and content interdependence.

4.4.1 Between supervisors: academic networking

Establishing a network then sending and grabbing information from it is how senior researchers interact with each other. Networking is no mere a single task. Rather, summarised from almost all my informants have reported, one should firstly 'sell' his/her own work to the public by presenting it in an attractive but also simple way. Then one needs to be a robust information collector and a shrewd analyser. Such kind of information includes what are latest research progresses and hot research questions, who are working on which issues, which laboratory has what techniques, what are top laboratories working on, and more important, what research questions are crucial and can be worked out by his/her own laboratory, what other techniques are required in order to establish this potential research, who are able to learn from or collaborated with, and so on. Finally one should build up interpersonal relation network with 'targeted' people, who are potential collaborators, as an academic 'diplomat'. In this vein, seniors take this part of sub-task of the project because in general they have, compared to juniors, more experiences and insights on the overall landscape of the research field.

Workshops, conferences and other meetings provide ample opportunities of such kind of networking. IDCT A started when the Bob came to Chris in the annual DFG meeting after the latter had finished presenting his group work. In the same vein, in the Team C, Ling joined in the collaboration with Chris when his former supervisor, who was a theoretical physicist and had already built up collaborative projects with the Chris, retired. Ling took over the role of his supervisor's so that continued the joint project. In short, they all found each other though this network.

This kind of network is a field of mutual reciprocity. Jack, a physicist PhD. researcher, reported:

We are in a small community. There are several research groups who are working on our area. My boss knows everyone [every boss] of them. Each year they exchange progresses of experiments, innovative ideas and new technologies by conferences...It is a network...when he *thinks one technology, even though it might be from other disciplines, will be required for our experiments, he asks the boss of the laboratory who has this technology for help. He will understand it by himself and teach us, or directly send us to the target laboratory to learn by ourselves. Of course we will also answer our collaborator's needs. Consequently it is beneficial to both sides because we do each other favors. (Jack)*

Moreover, interpersonal network needs to be maintained and developed, otherwise one senior will be left behind his/her colleagues in the area. Luckily, a network not only brings collaborators, but also promotes knowledge interactions, which in turn help extend the network. Will, the senior statistician in IDCT B showed me how his network was established based on continuously developing new algorithms and connecting them to other research concepts in the Figure 4.16.

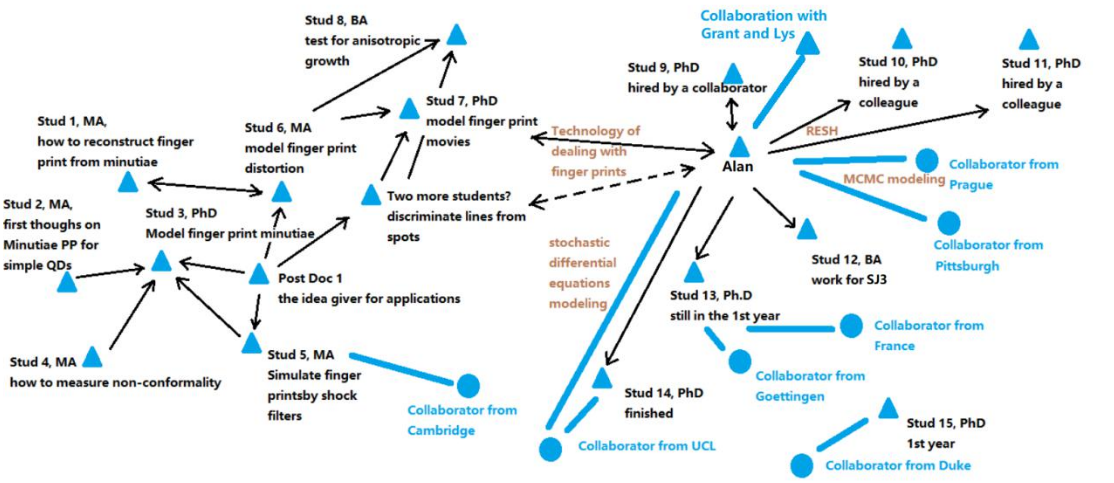

Figure 4.16 An illustration of Will's (the senior statistician in IDCT B) collaborative network

Note: Triangles represent his students and post Docs, while circles show his collaborators. Black arrows illustrate logical links among students. Logical links here mean that contents and/or methods studied by the arrow-end individual, which are colored in brown, employ those from the arrow-start individual. Blue lines represent that they are collaborating with scientists outside their groups, on certain research content or method, which name are also colored in brown. It is noted that Will does not show up in this map because all notes are linked to him. Alan is the junior researcher in IDCT B, Grant as senior physicist, while Lys as junior physicists in the same team.

The left part of the Figure 4.16 shows an almost-completed research project on fingerprints detecting and modeling. This is a collaborative project with a professor in the University of Cambridge. Will separated this project into pieces, for each he set to one of his master or bachelor student as his/her research assignment. Technologies of dealing with fingerprints as results of these small tasks included a software of detecting fingerprints and a statistical method of modeling movement of fingerprints called Markov chain Monte Carlo (MCMC). And then they were employed into Alan's collaborative study with their physicists collaborators in IDCT B. In a conference in Prague two months before this interview, Alan presented this result. And statisticians in the University of Prague showed their interests in this MCMC method, so that branch collaboration was conducting with them afterwards. As well, also in a conference Will met people in UCL whose expertise was in stochastic differential equation modeling. He '*outsourced*' (Will) this part of modeling by giving them his data and getting models as outcome. '*Outsourcing*' means that Will, in this vein, got the knowledge of this model as what it had already been made up.

Then he asked Alan to test this model by new biophysical experimental data so that Grant was able to build up biophysical models of actin stem fibers. By the time I conducted this interview, the Will had successfully established extra four to five collaborative projects with people from the US, France, Germany and UK. Most of these projects come from meetings and conferences – the social spaces that create ample opportunities for academic networking – in which the junior statistician formulate initial contacts and nail down initial collaborations with other senior members. More importantly, as oral discussion and email correspondence have been the main means by which the collaboration between senior researchers is initiated and put in progress, it is relatively easy to *'stage on the same page'* (Will) and agreement on how to move next is reached fairly quickly. In this way, they synchronously understand the current progress of an interdisciplinary project.

Also, Leo, the junior biologist in IDCT C, described me how his supervisor, the senior biologist, makes full use of this network:

We biologists can only do simplest regression analysis. But statisticians have various kinds of methods to describe the data in a more precise way. So as a professor [in biology] youlearn most from the first statistician you collaborate with than the tests. After finishing the first joint project, you know, Ah~there are so many statistical analysis that your collaborators can conduct, and you know their functions. So next time when you work with another statistician, you can directly ask him/her to deploy these methods. Because you always learn from people in your network, your knowledge is extended though working on interdisciplinary projects.

Of course sometimes people would not prefer 'next time another statistician' (Leo), yet rather keep a long turn of collaboration. Changing collaborators may not only cause instability to the progress of the interdisciplinary project, but also sometimes do harm to one's reputation. Shylock, who is the group leader of physicists of IDCT B, employed an ironic tone when he mentioned the former collaboration with biologists' group. He told me that the biologists would not continue the collaboration if they thought they had learned your techniques, even though in fact they did not.

Maintaining the network also means senior researchers of two sides need to negotiate about their own academic resources. They spend time on fixing research topics, applying research grants, writing research proposals together. Further, when the project is officially set up, they select and send their students to work jointly on this project. When students make troubles during their collaborations, supervisors stand out and make everyone satisfied. They are team collaborating leaders.

There was once when I was having lunch with Will, and his physicist collaborator Grant just past by and asked whether the statistician could avoid publishing his (Lys made it) new data on a collaborative paper done by the whole IDCT B. The key part of this little 'conflict' is about how to deal with the property of data. Apparently the data was collected by Lys, the junior physicist, who was supervised by the senior physicist. Moreover the data itself is already a publishable result in the vein of biological experiments. It means that physicists have the right to publish it first. But as collaborators they share this data to statisticians. So Alan analysed the data and had got some statistic results. The method he deployed had been creative enough for a statistic journal article. However, Grant wanted to use the data in another way: to compare analyses of this data to other data sets so that the team could publish analytic results to a biology journal. After carefully explaining the reasons to each other, and discussing with respective students,Will decided to agree with his physicist collaborator and to publish the analyses with the same method but with another set of data.

4.4.2 Between junior researchers: the 'zip' progress

Different from senior members, I use 'zip' process to depict how knowledge interaction takes place between junior researchers. The set of data is like a package, being sent, received and processed between junior biologist and statistician in IDCT C. Here I do not mean they are working with only one set of data. What is emphasised here is that one usually takes turns to deal with findings at different stages of analysis.

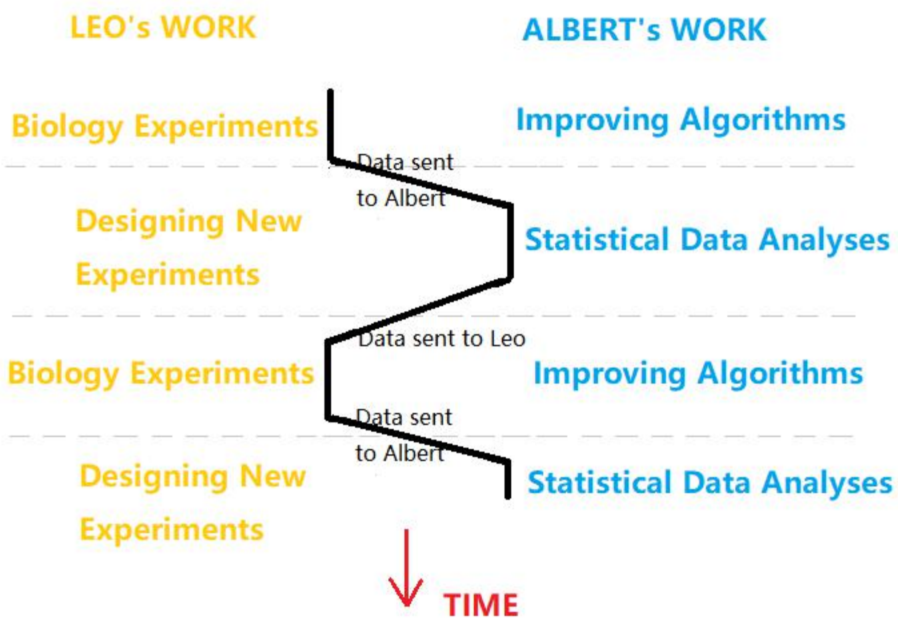

Figure 4.17 The 'zip' progress between junior biologist (Left as Leo) and junior statistician (Right as Albert). Note: From top to down what they are working on in their collaboration have been listed by time sequence. Orange characters describe Leo's work, while blue Albert's. Black lines going crossing between them track where data is processing.

From Figure 4.17, it can be observed that they are running a loop in the collaborative research procedure: the biologist makes experiments, hands in the data to the statistician, who analyses this data and sends them back to the biologist. He then conducts new experiments so that starts another round of the loop. This process will be finished until they have got enough analysed data that can be used to test their main hypotheses. Thus this 'zigzag' process illustrates the asynchronous process way of knowledge production where one needs to wait for the other's results for the next step of operation.

Keeping this 'zip' progress running smoothly, like playing Ping-Pong requires a perfect teamwork. However, a lack of synergy between collaborators may happen at the beginning of their effort.

When we met at the first time, the junior statistician even had not heard about cell, let alone cell skeleton, nuclei, and other biological details in the cell. At the same time, he gave me a long speech about mass of algorithms and math equations...But I told him that I did not neither need nor want to understand that math anymore. They were too much in details. What we in fact needed *to discuss was to clarify what the images I gave him were representing and what kind analyses I would need from him.* (Leo, the junior biologist in IDCT C)

In order to overcome this loss of synergy, senior researchers in the group meeting of IDCT C suggested the juniors increase the frequency of their meeting in order to solve the problem of in-synergy. '*Their tasks should be very clearly defined*', emphasised Chris. Thus Leo wrote down what kind of experiments he should do and what kind of data analyses Albert was supposed to do into tips and display them in a 'to do list'. He sent his statistician collaborator this list every week. Then in each weekly meeting they checked whether each of them had finished the tasks on the list and clarified new tasks in the coming week. '*Finally my collaborator got to understand what I needed him to do*' Leo released himself at last. '*After the second weekly meeting, we had been already on the same page.*'

'*I got to know how important we meet weekly. Otherwise Albert could have done so much works that may cost him great time, but cost us [biologists] only a little. He had already done some kind of this work*' Summarised Leo. 'N*ow we can exchange ideas and requires quickly. He told me my sampling frequency (10 seconds per image) is too low, which makes the resolution of images very low. So then I record two sets of data: image of every 2 seconds and every 5 seconds. He gives me feedback that 2 seconds works well for his program. Then I adjust the position and size of each video and cut off redundant information on them before I send them to my collaborator, which may make him easier to run analyses. And my supervisor does not even know that I have changed my recording frequency.*'

4.4.3 Between seniors and juniors: knowledge plantation

In IDCT B, Lys reported that the way of interaction between her and Grant was a loop of supervision: '*boss assigns ideas, she makes experiments*.' When she reports any trouble, the senior researcher helps her to solve the problem. Then she reports results, the senior discusses with her about what they can do with these results. Finally the senior assigns new task.

Metaphorically speaking, this supervision loop can be described as an interaction process called knowledge plantation. Supervisors as senior researchers grow the initial ideas (the 'seeds') into their students' minds. Then they nurture them, cultivate them by supervision loop, whilst students are paying hard working and learning. In this way, these ideas are growing up into buds, branches and then leaves, which represent that the first ideas are developed into hypotheses, then by making experiments, ideas are generated deeper into details and branches. Finally branches are bearing with fruits, which are picked up by supervisors in order to grow new seeds. In this way, students' minds are nurtured into 'more fertile soil', which are able to grow better fruits for next plants.

This interaction process can be illustrated by cognitive maps of the statisticians in IDCT C as a vivid example. Their story begins when biologists needed to recognise nuclei in videos automatically, they turned to Ling for help. The latter used his statistics knowledge to design a program in order to segment those nuclei by Gaussian shapes. Then Albert joined in the project. Ling asked Albert to employ his program to analyse videos for biologists, and to calculate trajectories of the movement of those nuclei. This is what Figure 4.9 and 4.11 demonstrate. Several months later, they found that trajectories of nuclei should not be tracked in a 2D plain image because '*some movements are impossible on the plain*.' (Albert) The fact is that nuclei are moving in a 3D curve so some of them are squeezed inside and some are gored out. So Ling believed that it was important to develop their algorithm to process image segmentation in 3D curved surface. Thus he assigned this task to Albert, who in the next two months looked at and learned from relevant literature and develop a ‘new method’ called ‘scale space’ (Albert).

From Figure 4.19 we can see that in the Ling’s map he only roughly mentioned about the target of conducting ‘statistical analysis in 3D’ to track ‘trajectories’ of nuclei. But he did not give more details. As we have known, it means that the senior had assigned this research target to the junior. In Figure 4.18, Albert claimed the ‘new method’ to detect ‘potions of particles’, representing that he had been working on this issue. In other words, the senior had grown a ‘seed’ of developing a new method in the junior’s mind at this point.

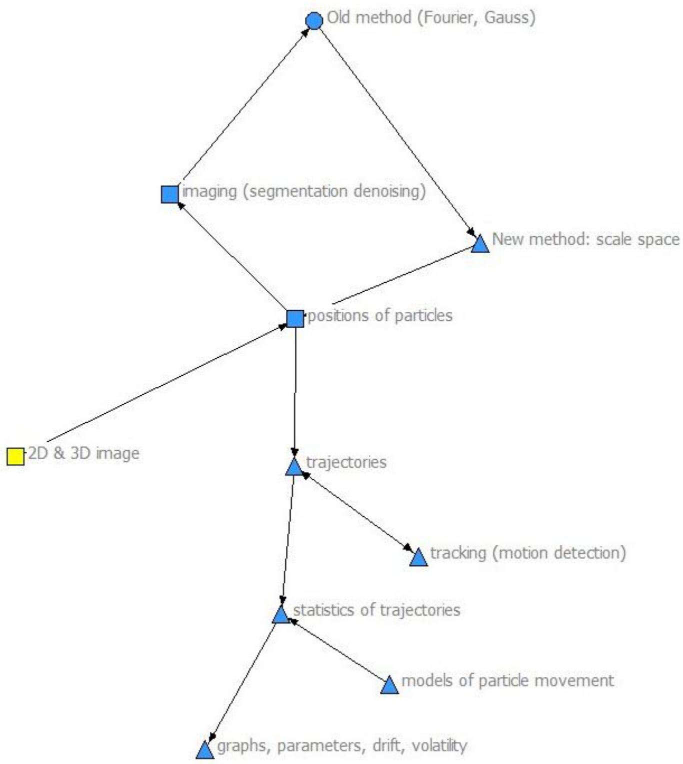

Figure 4.18 Cognitive map of the junior statistician in Team 4 at his second stage. Shape and color principles are the same as in Figure 4.3.

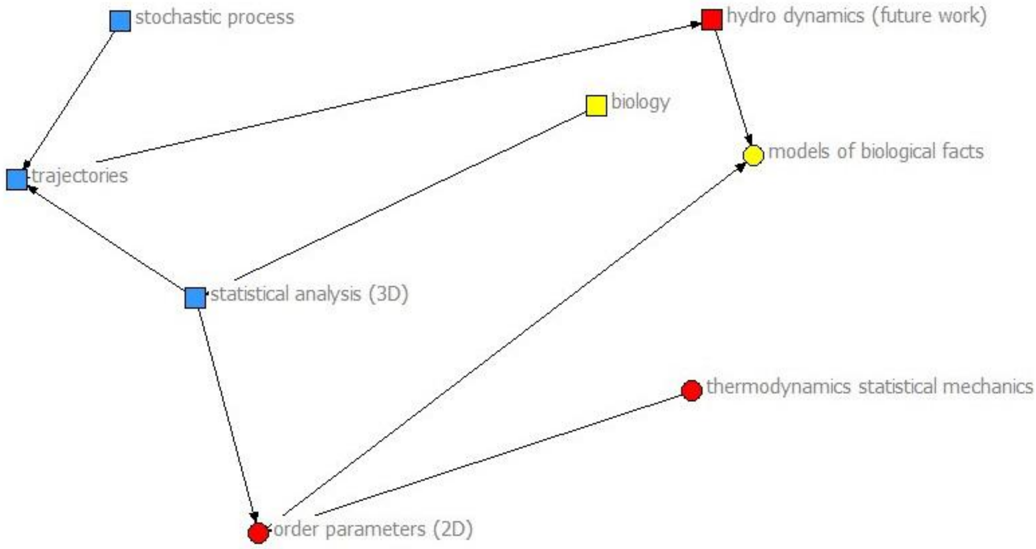

Figure 4.19 Cognitive map of the senior statistician in Team 4 at his second stage. Shape and color principles are the same as in Figure 4.3.

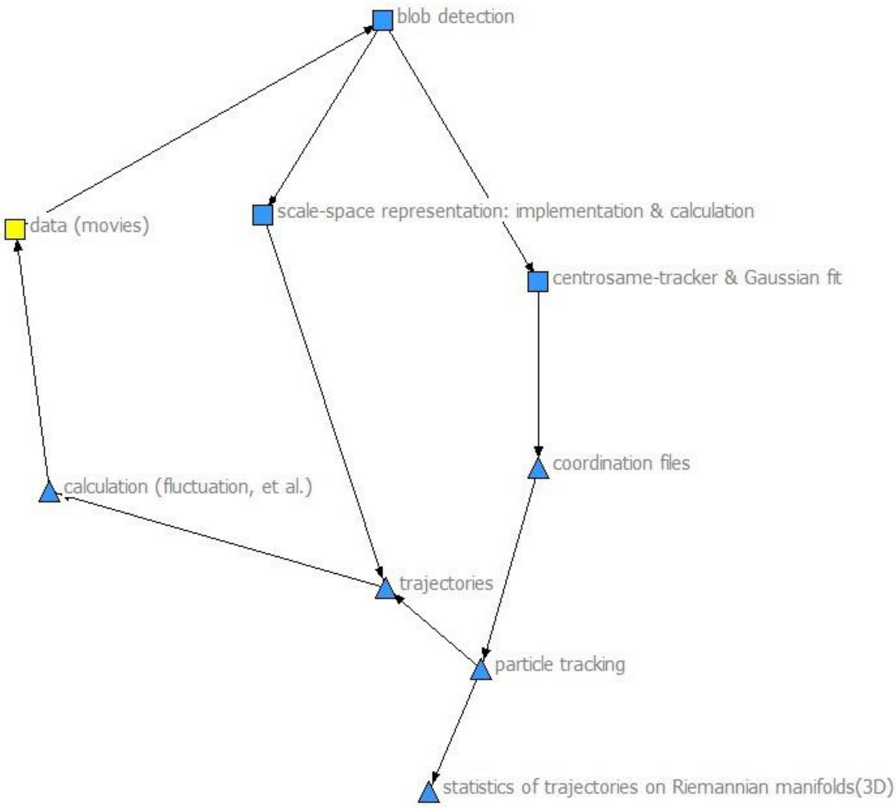

Figure 4.20 Cognitive map of the junior statistician in Team 4 at his third stage. Shape and color principles are the same as in Figure 4.3.

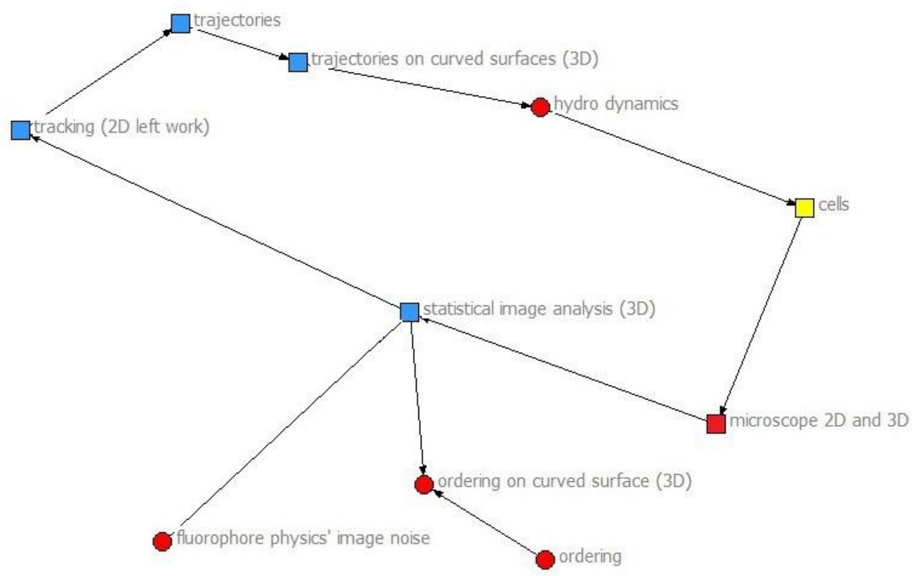

Figure 4.21 Cognitive map of the senior statistician in Team 4 at his third stage. Shape and color principles are the same as in Figure 4.3.

When Albert had successfully found a way of 'scale-space representation', which has been illustrated in Figure 4.20, he could finally employ 'statistics of trajectories on Riemannian manifolds (3D)' to track 'trajectories' of 'particles', namely nuclei. This result of course had been admitted by Ling, who displayed new nodes named 'trajectories on curved surfaces (3D)'. Compared with Figure 4.19, this is a more detailed description on the statistical method to conduct '3D image analysis'. In this way, the 'seed' has been grown up and fruits have been picked up by the supervisor. Consequently, in Figure 4.21, it can be seen that notions like 3D statistical image analysis have already shown up in the senior's cognitive map.

4.5 Discussion

This chapter reveals the division of labour among scientists in IDCTs as well as interactive modes between each pair of senior researchers, of juniors and of a senior and a junior in the same discipline.

In particular, senior researchers play with networks and consider only general and big story of the project; junior researchers collaborate like ping pong playing by zipping data process; whilst between the senior and the junior researchers, the former grow ideas into the latter's minds, nurturing them and pick up the fruits by supervision loop, which makes the interaction a process of plantation.

This chapter teases out that hierarchical difference of researchers is associated with how people organise both of content interconnection and task synergy of their IDCTs. Whilst, different from what Whitley (1978) has found out, the disciplinary distinction of researchers merely relates to the extent of content interdependence, yet surprisingly not to how to make progress interdependently in finishing sub-tasks of the project. These findings suggest, as this chapter argues, that in these IDCTs, disciplines only play a role in maintaining the uniqueness of respective research contents. However, the way to organise inter-task connections and integrate research contents from various disciplines is depending on the organisational property, namely the hierarchy system, of an IDCT. This is also what previous discussion on 'Mode 2'-like (Gibbons et al., 1994) ignored.

Yearley (1990) argued that it is scientists' choices and negotiations rather than intellectual structures (Whitley, 1983) that form up social organisation of scientific researchers. He claimed that knowledge produced by cognitive activities was 'shaped by scientists' choice of work organisation' (Yearley, 1990: 329). Findings in my case study is distinctive from both of theirs: compared to Whitley, who was focusing on macro-level scientific disciplines, the scale of this research is in micro-level interpersonal communications; against Yearley, I claim that the cognitive structures of scientists play a crucial role in establishing IDCTs. The asymmetry of resources and academic ability, which is deeply rooted in researcher' minds, may also serve as reasons of the found relationship between the hierarchy system and research interdependence. After all, seniors' works concern general and constructive efforts on the whole research project generated from their academic networking, whilst juniors' works include merely specific data collection and analyses fixed within weekly discussions. Unlike most senior researchers, comparably less experienced juniors believe themselves and are believed, at least temporally, lack of ability of understanding the whole picture of the project, that is, the overall knowledge network from which latest and innovative topics emerge and are picked up. Consequently, it is '*natural*' (Ling) that contents of research workload as well as related arrangement of work sequences are divided in ways found here. Juniors have to bury themselves into practical and detailed daily dirty works in order to accumulate experiences and expertise because seniors who are able to arrange huge research projects do not have time to work on these. Plus what have been introduced about the authorisation on right of research funding applications, seniors may assign the same task to other juniors but the latter cannot work on the project if without the former. In this vein, seniors get more priority and advantages in this pair of relationship (Latour and Woolar, 1979), which implies that the interdependence between the two counts hardly a mutual one.

Against the idea of decoupling interdependence between tasks from between agents (Puranam et al., 2012), this chapter claims that multiple types of task interdependence has been found at work in one same team. It has been found that seniors deploy synchronously simultaneous interdependence as oral discussion and email correspondence have been the main means by which a collaboration between them is initiated and put in progress, it is relatively easy to 'stage on the same page' and agreement on how to move next is reached fairly quickly. Unlike their bosses, the 'zip' process illustrates the asynchronous reciprocal interdependence of knowledge production where one junior needs to wait for the other's results for the next step of operation. A loop between seniors and juniors exists in the circle of growing 'seeds of ideas', working and developing on those ideas and harvest results.

The 'zip' process also claims a similar way compared to the 'sequential oping-up and closing-down' mode of governance. The latter (Figure 4.22, left) describes a process, in which based on given goals and problem definitions, a group of heterogeneous participants at first work on multiple dimensions of the task then, through diverse interactions, are led converged into a common new strategy for problem handling (Voß et al. 2006: 434). They are similar because it is fair to consider weekly group meetings taken place by the two juniors of an IDCT as the interaction process between opening-up and closing-down. Before and after the meetings, they are exploring the same set of data from various dimensions: one side works on data collection and the other data analyses (Figure 4.22, middle). But in fact the group meetings function as merely checking up work progresses and exchange requires and needs, which can also be finished without the meetings. In other words, if the two juniors are already quite familiar with each other and have geared their work progresses perfectly, they can just smoothly run multiple loops of ‘data collection-data analyses’ without any need of meeting up (Figure 4.22 right).

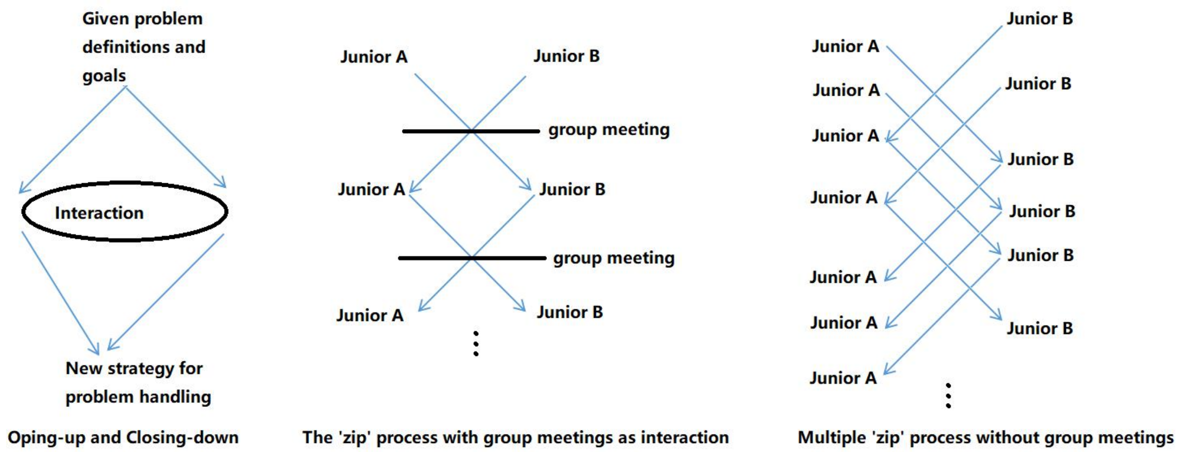

Figure 4.22 A comparison between ‘opening-up and closing-down’ mode of interaction and the ‘zip’ process, with and without group meetings.

Chapter Five

The Efficiency and Effectiveness of Interdisciplinary Teams

This chapter sheds light on the issue of efficiency and effectiveness of the interdisciplinary collaborative teams (IDCTs). In the first part, it examines the efficiency of works and communications of IDCTs. In particular, it analyses all the potential 'benefits' and 'costs' (Katz and Martin, 1997; Landry and Amara, 1998; Lee and Bozeman, 2005) embedded in every stage of IDCTs. Through this analysis, a comparison between two kinds of IDCTs abstracted respectively from the 'CSP' group and the 'BPS' group has been conducted in order to elaborate that the latter works more efficiently than the former. In the second part, by plotting the creativity and utility of the knowledge systems bared in scientists minds, two modes of innovation, namely functional and totalised distribution of innovation has been found. These two modes combine in each different ways of contribution on innovation by scientists from various disciplines and hierarchical positions in the IDCT.

5.1 The issue of efficiency of IDCTs

5.1.1 Benefits and costs: a tacit calculation among collaborators

Academic communication, the way that researchers talk to and negotiate with each other, is not as easy as it looks. On the contrary, as Chapter Three and Four have briefly indicated, different IDCTs may have different communicative strategies to make the collaboration possible and to make the daily operation of collaborative research go smoothly and efficiently.

Before this chapter proceeds further, it is necessary to clarify the definition of efficiency discussed here. According to Landry and Amara (1998), the issue of efficiency in a collaborative research can be investigated at three distinctive levels: at the 'researchers' level', it is calculated as the ratio of cost/benefit of scientific operations; at the 'collective structural level', this ratio can be examined upon various ways of organising research teams; at the 'national level', efficiency means how much research outcome per a certain amount of research funding (1998: 906). In the collaborative team, the 'benefits' of research activities like publication are normally presented in a collective form. In addition, as previous chapters have revealed, many costs have been paid on communications among IDCT participants, which happens not only at the researcher's level, but also at the collective level. Consequently the efficiency discussed in this chapter is at the above-mentioned second level.

Followed this definition on efficiency, costs in the context of IDC refers to time, energy and money scientists pay for conducting interdisciplinary researches and communicating within and beyond disciplinary boundaries. In this chapter, merely coordinating costs caused by IDC are considered because producing costs are paid also in single disciplinary researches. Benefits are new research abilities, more academic resources and production of knowledge through IDCs. Both costs and benefits will be discussed in details in the following sections.

Before we go into theoretical analyses on efficiency of IDCTs, let us review the ethnographic cases of ‘CSP’ group and ‘BPS’ group again. One of the difficulties that was reported during the fieldwork is the different work paces manifested in different collaborators. For example, Yann was fed up by the fact that he had been waiting for Weiss’s result of computer simulation yet Weiss did not prioritise the collaboration as much as Yann expected. As a result, Weiss’s delay interrupted the ‘rhythm’ of Yann’s expected quick turnover from data collection to analysis results. Clearly Yann was making a careful and rational consideration between time and result (in this case, publication), just as he complained, ‘*it had been over the budget of time*’. To him, to work with who was not just a question about research compatibility, it is also about work pace and communication efficiency, that is, how can a team work better in the limited allocated time slot.

Similar consideration on work efficiency and communications can be found in almost every member of the ‘CSP’ and ‘BPS’ groups; however, these calculations on intellectual and time input and research output (including, for example, publication) are not explicitly expressed by every scientist. These are the tacit and unspoken side of the collaboration. Even though it seemed that nearly every scientist had his/her list of work priority, none of them were willing to explicitly talk about it in the public meetings, or reveal this list to me. As Jack, a junior physicist as one of extra interviewees in the ‘BPS’ group, said to me: ‘*you want to know how the bosses arrange their time in order to get best benefits on publications? This is impossible! Because the strategy of their personal career development is classified on the top of their list of secrets!*’

In a highly competitive academic environment, Yann told me that his time should be devoted to one thing, publication, with detailed requirement on the number and quality of publications stated by his department. As a contract-based PI, he knew too well the importance of publication in the culture of ‘publish or perish’, and become extremely pragmatic with IDC projects. His best interests from the IDC project, like some others, were to conduct a number of good publications on top journals, and to nurture long-term trusty relationships with other group members. His acute sense of time and its values can be best illustrated by the way he came to join my investigation. At the beginning, when I sent my request for an interview with him, he gave me five minutes to persuade him to spend his ‘*most valuable thing of life, which is time*’, on my investigation.

Yann was extremely careful with time and energy allocation during a day. Occasionally, he forgot to reply my email requests for regular interviews. Once I complained about his ignorance on my requests, he did not answer directly but told me a long list about various situations that different collaboration types may occur. He treated it so carefully that he asked me to turn down the recorder before told me the list. On the top of the list located potential collaborations that result in a Science/Nature paper, followed by normal academic researches for which his collaborator repeatedly ask for appointments. Works required limited time investment with the payback of normal publication as output were ranked as the third. Issues like volunteering his time on an investigation of a doctoral student apparently are put around the bottom of the list. He emphasised repeatedly that what he studied should be real scientific researches. And being aware of a real and good collaborative scientific research costs time. In other words, Yann faced the tension between a well-organised collaboration and efficiency of productivity (Lee and Bozeman, 2005). Indeed, he might not be happy with Weiss’s delay of the result of simulation. But if he quit from discussions on general direction of the project and left the group, all his previous time that had been spent on building up trust and understanding academic languages of other group members would be lasted in vain.

In the ‘BPS’ group, by contrast, the stress of publication seemed to be distributed among several group members. At the cognitive level, senior researchers in the ‘BPS’ group had established the framework of a whole team and reached an agreement on boundary objects, namely the set of technologies, theories, skills or equipment they shared as the ankle of the whole DFG project. In this way, junior researchers needed not take care of the direction of the project nor forming up the team. At the interpersonal level, potential conflicts like waiting for delayed new data had been transferred into interactions among junior researchers, who conduct research jointly by the ‘zip process’. Whilst senior researchers were able to push their students so both of the seniors and juniors had shared that pressure from the ‘publish or perish’ doctrine.

Even though both junior and senior researchers worked on building up the IDC team as well as making progress on the joint research efficiently, there seemed to be not a tension between them at all. In other words, researchers had enough time for taking care of good interpersonal relationship with their collaborators through the project team and at the same time, conducting real interdisciplinary research in a satisfied speed by networking or by ‘zip progress’.

However, it is not true to claim that scientists in the ‘BPS’ group do not make any explicit calculation on benefits and costs. Grant, a senior physicist introduced in Chapter Four, made an extremely exaggerated expression on his face when he was noticed that my face-to-face interviews might last for thirty minutes, which was not ‘*thirteen minutes*’ as he expected. His question implied that he would not invest ‘so much’ time doing me this favor, from which he would got much ‘benefit’ at all.

It is clear to see that underneath the common phenomena of ‘delayed collaboration’, there are complicated calculations which are dependent on time, trust, working style, the number of research projects at hand and publication timeline. All of these potential considerations may be mistakenly put into one excuse ‘unsynchronization of work’. This leads us to regard the effects and fluency of communications as a complex game that each player carries out his/her own calculation of time and interests and their work priority.

If we make a blunt comparison on the communicative operation between ‘CSP’ group and ‘BPS’ group, ‘CSP’ group had difficulties in pushing the collaboration forward at every step and had only two joint publications (including one bachelor dissertation) from two IDCTs while ‘BPS’ works smoothly and publishes seven papers (including three doctoral theses) all together from three IDCTs. Certainly, publication is dependent on various issues, including the different cycles of academic publishing. But it is crucial to see how efficiency has played a significant role in establishing and maintaining the interdisciplinary collaboration. In what follows, I will carefully map out all the potential benefits and costs that are embedded at different stages of an interdisciplinary collaboration, including the stage of potential collaborators’ match-making, the operation of daily collaboration work, and the final output of the collaboration and the individual claims on credits. It shows that the ‘CSP’-kind, which merely consists of senior researchers, and the ‘BPS’-kind, which consists of both seniors and juniors may lead to different game setting about efficiency.

5.1.2 Benefits of IDC

In general, prior studies claim that benefits of IDC include the ability of solving complex research problems that beyond one single disciplinary knowledge, high creativity, the production of knowledge that is not only insightful to academic communities but also valued in the industry, an integration with multiple research methodologies and so on (Frodeman et al., 2000; Collin, 2009).

However, just like Yann has pointed out, rather than above-mentioned benefits defined in a general way, scientists in IDC efforts are in fact considering more practical ones. Just like what Faurot and her colleagues (2013) found out, faculty members may distribute their time depending on weights valued in the tenure and promotion process. Thus it is reasonable that they would spend more time on works that may result in more publications than receiving my interviews. In addition, Katz and Martin (1997) reported that a research collaboration costed money, time and increased administration in order to get the benefits of sharing and transferring of knowledge and skills, a cross-fertilisation of ideas that brought new insights, as well as intellectual companionship. Landry and Amara (1998: 903) summarised the following benefits of academic collaborations: network building among collaborators, additional funding, equipment, facilities, information and data, resources, increase in the number of publications, innovations, in the quality of teaching and training and in the possibilities of employment for students. Obviously, many of these benefits are double-edged swords because they also cost extra time and administrative burdens.

The above-mentioned benefits can be located into Latour and Woolar's cycle of credibility (1979). They claimed that funding, research networks, equipment, data, research problems, publications, and so on were exchanging from one form to another as an endless cycle of capital reproduction.

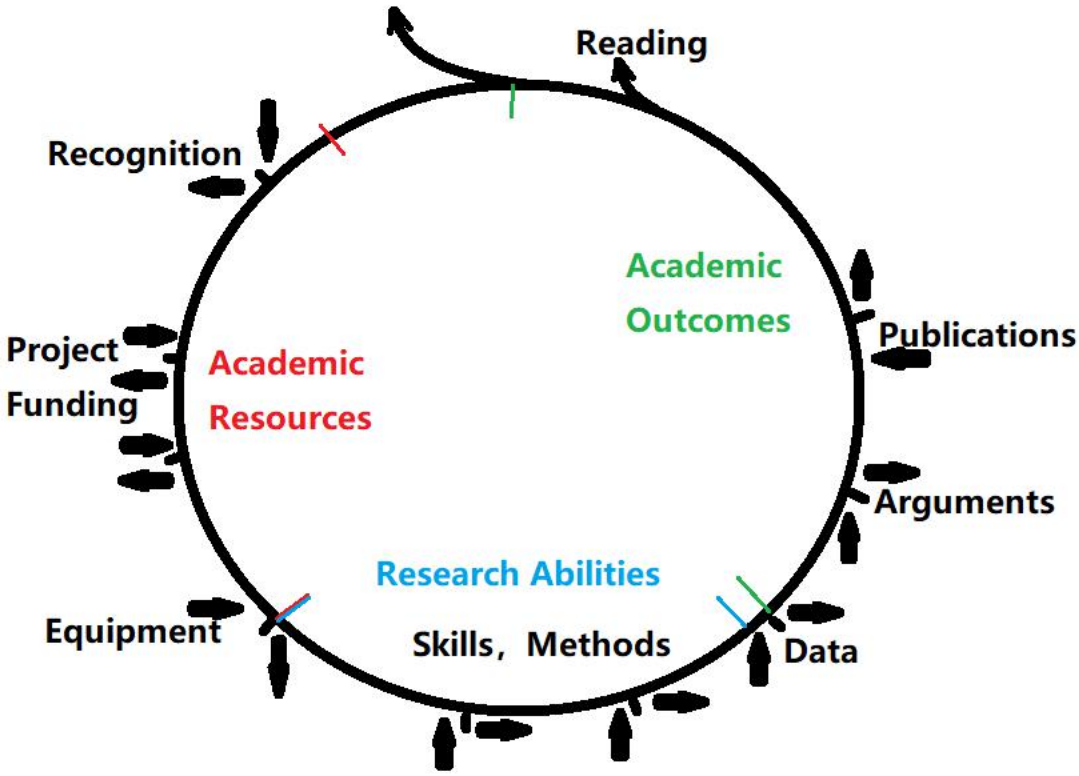

Figure 5.1 Recycling of academic capitals. Revised from Figure 5.1, Latour and Woolar, 1979. *Laboratory life: the construction of scientific facts*. N.J: Princeton. pp. 201.

I argue that it is reasonable to categorise these practical benefits into three inter-related sets: more academic resources (project funding, person-power, network, title promotion), new research ability (new perspectives, equipment and skills) and advanced academic outcome, that is co-publication. Communication endeavour like forming up consensus on shared scientific notions and research topics, building trust, dealing with misunderstandings and setting up regular meetings that maintain an IDC can be seen as sub-tasks achieved for the validity of the research abilities and for potential academic outcomes. In this vein, they can be partially treated as benefits. As shown in the figure 5.1, one category of practical benefits can be derived from another as more resources can be used to enhance stronger research ability, which probably lead to higher quality or quantity of publications. With these publications, one can apply for more sources.

5.1.3 Transaction costs in IDC

5.1.3.1 Defining transaction costs

The nature of Yann's calculation on time investment, this section claims, is scientists awareness of transaction costs paid for IDC. The economics concept of transaction cost has been established by Coase (1937) and later developed by a branch of talented economists (Arrow, 1969; Williamson, 1975, 1981, 1985; Williamson and Masten, 1995). Arrow defined this term as the 'costs of running the economic system' (1969, p. 48). Unlike production cost, which describes resources being paid during production of goods, transaction cost exists only when a transaction is made.

Distinctive perspectives on transaction cost are emphasised by defining this concept in various contexts. First, with Arrow's definition on the transaction cost, Cheung (1998) studied the cost of the system that sustains transactions. This cost that has to be paid to accomplish transactions may be caused by laws, institutions of the state, social and cultural environment and so on. Sá (2006) has mentioned that institutionalised structures of disciplines and departments may be one source of the transaction cost of IDC efforts. However, this is not the perspective we are discussing here. As this research is conducted in only one university, the institutional environment keeps steady.

Secondly, Cheung (1969) and Allen (1999) paid attention to the cost spent on maintaining property rights of goods. This perspective is neither ours because by the rule of communism in the academic community (Merton, 1973), knowledge should be accessed by all human beings, except for patents protected by law and classified national secrets, both are out of consideration of this dissertation. Thus what is rewarded and valued in academia is the right of first discovery, which is pursued by publishing new findings before everyone else. When having published an article on a journal, authors pay no cost to maintain it published.

Thirdly, Williamson's focused (1985) on a specific transaction and examined the cost paid before and after a transaction was made. For instance, before a transaction, there is a need to search for traders and reliable goods, to spend time and energy on bargaining and fixing a price, and to make a contract; behind, attentions and money is paid on testing quality of goods and other services. All these steps produce transaction costs, which make a transaction no longer a simple process of just good exchanging. That is why it is also metaphorically called as 'the economic equivalent of friction in physical systems' (Williamson, 1985: 19). This is exactly what is studying here, as Sá (2006) and Phirman and Martin (2010) have also mentioned about the cost of time and energy that is spent on understanding knowledge from other disciplines and establishing common language via communicating within an IDCT.

In both of the 'CSP' and 'BPS' groups, it is evident that many informants explicitly deploy a transitional perspective in understanding the nature of collaborative research. This is evident in how specific tasks are allocated within the team. For example, some collaborators would stand out and voluntarily take more workload to ensure that other members take a good use of the gained time to focus on more crucial issues that yield in more potential ‘benefits’. It is also found that if a scientist finds out that the transaction costs of collaborators from other disciplines are higher than expected, this scientist would rather drop out the collaboration. In other words, scientists in IDCTs decide whether they take part in a collaboration or not and how long they focus on it by estimating potential transaction costs on this particular communication.

For example, Leo, a junior biologist in ‘BPS’ group, perfectly explains to me why transaction cost is useful to understand the IDCT members’ conception on time and efficiency in the collaboration:

‘*Bosses are very busy. They need to take care of so many different issues at the same time. Thus sometime I would rather take over all technical works, because bosses should set up the directions of the project, which is definitely one of the most important things, with their collaborators. But they do not have enough time. So I can make time for them...so it is still reasonable when you cannot hear from Bob, the senior physicist as one of our collaborators, for a month, even though when we need him. He must be busy working on other projects [when he vanishes].*’

Yegros-Yegros and his colleagues (2015) listed that an IDCT might serve as a means of creativity and innovation and of solving problems more successfully. Whilst costs of IDCs contain efforts forming up shared language, norms, organisational cultures, physical locations and the consensus on a division of work load and schedule. The cost of time and money have also been found crucial for running an IDCT (Katz and Martin, 1997; Faurot et al., 2013). In this vein, an IDC effort can be viewed as an exchange of three kinds of benefits, namely ability, resources and outcome, with the transaction cost of money, personal time and energy.

5.1.3.2 Transaction cost analyses on IDCTs

So what factors can be considered as ‘transaction costs’ in an IDCT?

By starting with, we consider IDCTs with only two senior researchers from two distinct disciplines. Costs that have already been listed by previous studies include money, time and energy for increased administration (burden) at the institutional level; for relationship maintaining, authorship bargaining, and working on the same pace at the interpersonal level; for overcoming disciplinary as well as physical differences; and for building up common interests at the cognitive level (Kahn and Prager, 1994; Katz and Martin, 1997; Landry and Amara, 1998; Pellmar and Eisenberg, 2000; Jakobsen et al., 2004; DuRussel and Derry, 2005; Cummings and Kiesler, 2005, 2008). Further details are displayed as followed:

Increased administration burden

First, interdisciplinary efforts cost extra resources of disciplinary based departments in terms of office space, department funding, working labour and usage of equipment like microscope, chemicals and computers that could, if not occupied by the IDC project, have been used to conduct studies merely inside the discipline (Maton et al., 2006). Secondly, secretary of the disciplinary based departments need additional communications with other disciplinary departments if an IDC project is supported by both sides. Thirdly, as the evaluation system of academic researches has been deeply rooted in professional discilinary-based academic community, it increases the hardness of being accepted if an interdisciplinary work is to published disciplinary-based journals (Jakobsen et al., 2004). In addition, as the quantity and quality of publications have been solidly associated with personal promotions of research positions in departments, it requires more efforts to evaluate interdisciplinary academic reputation of the faculty and PIs. These burdens are close to system transaction costs by Cheung's definition (1998). In order to theoretically compare the cost differences between IDCTs of the 'CSP' kind and of the 'BPS'-kind, I assume that both teams face the same situation on these above-mentioned factors.

The establishment and maintenance of collaborative Relationship

First, in order to meet up with a potential collaborator from a foreign discipline, senior researchers need to extend their networks though conferences, workshops, and network of their colleagues' and collaborators' (Ziman, 2000; MacMynowski, 2007). Also, it takes huge amount of time and energy of senior researchers to not only understand their potential collaborators but also make sure that they are worthy of work with (Agger et al., 1997; Jakobsen et al., 2004). Prior experience of collaboration help to reduce the negative influence of disciplinary difference (Cummings and Kiesler, 2008). Second, researchers need always to build up trust upon each other by showing great interest and enthusiastic attitudes to the potential project, communicating about the progress frequently, and listening and answering each others' questions and requirements in a proper manner (Cummings and Kiesler, 2005; Maton et al., 2006; Stamp et al., 2015; Bendix et al., 2017). Finally, supervising students, as has been widely studied, costs time and money of supervisors. (Seymour,et al., 2004; Desai et al., 2008; Thiry and Laursen, 2009, 2011; Dolan and Johnson, 2009; Reddick et al., 2012; Faurot et al., 2013).

Working on the same pace

First, due to the difference of time cycle of knowledge production, IDC participants need to adjust their expectations on the speed of work by collaborators from other disciplines. Yet not all of them realised the need of this adjustment. Consequently, extra communications are required to fix misunderstandings between group members and suspicions of the progress delay, laziness and unwilling of participation. In order to overcome this problem, a creative way of integrating multiple ways of knowledge production in participant disciplines should be designed so that the 'zip process' is able to be archived (Jakobsen et al., 2004). Second, due to the difference of ways of organising teams in respective discipline, IDC participants may also spend time on deciding whether they should stand in the same status or they will employ a hierarchical team structure. If the latter has been chosen, further organisational issues like who will be the leader and who will be the member(s) should be discussed (Jakobsen et al., 2004; MacMynowski, 2007).

Authorship bargaining

First, what kind of and how much information should be included in an article differs from one discipline to another (Jakobsen et al., 2004). In 4.4.1, an example has been given by the discussion on between Chris and Will. This negotiation process is time consuming. Second, there are different cultures about the sequence of authorship in a published article. For natural scientists, the unspoken rule goes as junior researchers who do practical works are listed as first authors and senior researchers as supervisors and bosses should be listed at the end of the list as communicative authors. In comparison, in social sciences, who claims the core ideas of the paper should be listed as the first author or even at the same time the communicative author. In some discipline, author names are listed by the alphabet sequence. This difference of rules may result in conflicts and misunderstandings, which need time of IDCT members to fix up (Maton et al., 2006).

Differences among knowledge disciplines and common interests

First, a senior researcher needs to consider what are the details of other disciplines that he/she can ignore, what are those he/she must understand in order to know how to connect the two different knowledge systems, and what are general ideas that he/she may employ to develop into the direction of the project with the consensus of collaborators. It is not easy for all participants to set up their own communicative strategy because discussions at the kick-off meetings may be a mixture of both details and general ideas. Second, as what have been shown in Chapter Three, to understand each other's research needs, methodology, disciplinary language and concepts has already been time consuming (Jakobsen et al., 2004; Stamp et al., 2015). However in order to come up with a proposal that meets common interests, researchers need to pay much time and energy to fulfil the process of conceptualisation and integration of shared topics.

The above-mentioned 'sweet' burdens caused by IDC efforts will end up being a kind of advantage and beneficial output only if they have been gone through. It might be not so hard for an unofficial research team, made up by two or three experienced scientists, some of whom may have studied on the target topic for years and have established a very specific requirement for collaboration, conducting weekly face-to-face meetings 'with no telephones, no interruptions, and just talk[ing] about things' for years to establish a high standard IDC study (see the case of Grant, 2007). That said, for those who are under pressure of strict three-year's verification from grant committee or of personal title promotion in the academia, such a luxurious freedom of 'just talking about things' is beyond their expectation. They are not only busy squeezing time to think of their research ideas and conducting a couple of analyses, but also spending a huge amount of time dealing with daily, routinised or organisational issues. Luckily, ideas and organisational issues can be done by thinking lonely, discussing with colleagues and sending orders to secretaries and students; while data collection and analyses, no matter based on computer programs, fieldwork, or experiments, require practical activities. This difference of property between mental and manual labour, on which scientists pay their time to work, provides probabilities for IDCTs to embrace a division of labour to solve the tension between a well organised collaboration and efficiency of productivity.

5.1.4 A comparison on the efficiency of two kinds of IDCTs

Now we extend the group size into four members and set up two kinds of IDCTs: besides the two initiative senior researchers, we suppose that there are each of the discipline two extra researchers: they are two seniors in the IDCT in the first kind (like 'CSP'), and two juniors in the second kind (like 'BPS'). For convenience, I name the first kind of IDCT as the 4S IDCT and the second as the 2S+2J IDCT. An additional difference is that the two senior researchers in each discipline in the 4S team are independent; while each pair of senior and junior researchers in the 2S+2J team work as a disciplinary team; juniors are employed through contracts by the seniors. In this way, the two modes share the same group size and the same distribution of disciplines.

Further, as has been claimed in 5.1.3.2., we suppose that both of the two kinds of team are facing the same situation of increased administration burden. In addition, we assume that they are holding similar personal characters, using English as the work language in scientific researches, and staying at the same university. Last, we suppose that they are accepting the same amount of financial support by project foundations like DFG. In doing so, we are able to focus on the potential benefits and costs in the development of the IDC project.

It is to be noticed that Katz and Martin (1997) discussed another way of division of labour: only senior researchers contact with each other, with each of their junior collaborators only responding to themselves. This kind of collaborative mode is not considered here.

In this section, I try to illustrate these calculations based on evidences provided from interview reports and daily behaviors I have observed by participant observation. It should be noticed that not all listed benefit-cost analyses were conducted by every team member of an IDCT: Some calculations on benefits and costs were hidden by my informants on purpose; some were made by my informants without their self-awareness. These benefits and costs may also be weighted differently, depending on informants' experience and their careers development.

The key difference between the two kinds of IDCT is to separate the technological and specific operations between junior researchers from epistemological and theoretical discussions between senior. In the 4S team, both of these works are done by all senior researchers; while in the 2S+2J team, they are divided and assigned to people in different positions, which have been clearly introduced in the Chapter Four. With all of the above set up, the following part elaborates how the division of scientific labour described in the Chapter Four helps to produce scientific knowledge efficiently. Please see the results summarised in Table 5.1.

Table 5.1 A comparison of the efficiency of two kinds of IDCTs

Tasks	**Comparisons of the efficiency of two kinds of IDCTs**
Finding proper collaborators	E (4S) > E (2S+2J), for in-experienced junior researchers
	E (4S) ≈ E (2S+2J), for experienced junior researchers
Forming up mutual understandings	E (4S) < E (2S+2J)
Meeting up for the maintenance of the collaboration	E (4S) < E (2S+2J)
Dealing with misunderstandings and flaws	E (4S) ? E (2S+2J), for in-experienced junior researchers
	E (4S) < E (2S+2J), for experienced junior researchers
Building trust	E (4S) < E (2S+2J)
Working on the same pace	E (4S) < E (2S+2J)
Bargaining on the authorship	E (4S) < E (2S+2J)

Note: E (4S) represents the efficiency of 4S IDCTs. E (2S+2J) represents the efficiency of 2S+2J IDCTs.

Finding proper collaborators

At the initial stage of establishing an IDCT, the main goal is to find proper collaborators with whom a scientist is able to run a joint project. To obtain such academic resources as benefits, the costs of senior researchers and juniors can be compared from the following four perspectives.

The first perspective is personal experience and ability. Seniors are more experienced in networking and establishing collaborative relationships, simply because normally they have attended much more meetings and have taken part in more research projects than the juniors. The second is the amount of resources that people are able to obtain from their personal academic networks. It is reported by my informants that juniors' networks are connecting with less information, resources and familiar collaborators with prior experience of working together than the seniors'. The third perspective is the quality of resources on interpersonal relationship networks. Because in natural science, juniors are considered as belonged to a laboratory or research group of a senior, they are hardly able to generate collaborative relationships without mentioning their 'bosses'. This implies that seniors generate networks among seniors and that most population in juniors collaborative networks are juniors. Besides, Leo told me that information got by junior researchers' networks were more practical, in terms of what laboratory had what kind of equipment and technology, than by seniors' which included not only available resources but also sparking theoretical ideas. Forth, it has been found that higher level researchers are more encouraged by the policies than junior ones to establish a collaboration (Katz and Martin, 1997).

In this vein, because from every perspective the seniors have greater opportunity and more resources than the juniors, it is deducted that it costs less time of the seniors than the juniors to find proper collaborators and to establish an IDCT. Thus on this point, the efficiency of 4S team is higher than of 2S+2J team. With juniors' accumulation of experience on building networks and integrating resources, the gap of efficiency of two kinds of teams may be narrowed.

Forming up mutual understandings

It happens more on seniors than on juniors that one is constrained by his/her own research area, namely prefers to search for only inputs by taking part in the IDCT in order to develop his/her own study. Scientists with this purpose are keen on holding their own understandings on certain notions and projects, upon which mutual understandings should be formed up if a joint research takes place. In this vein, juniors researchers, who are likely to be with opener minds and are easier to accept ideas from other fields than the seniors. In other words, they have higher willingness and ability of sharing knowledge, which make their communication more efficient.

Meeting up for the maintenance of the collaboration

An IDCT, after its establishment, has to be maintained by meetings and communications. Stamp and her colleagues (2015) reported that there was need to set up a frequent and clear communication among IDC group members, which had been found bring trust and efficiency, and eventually ensure the productivity. Thus taking the maintenance of an IDCT as a benefit, the costs can be examined by the frequency of communications and by salaries paid for juniors and seniors. In the 'CSP' group, Yann, Weiss and Marilyn's group met nearly every week. In the 'BPS' group, juniors discussed on the same sequence and seniors paid only one day per month for group meetings of one single project. Whilst, communications between junior and senior researchers happened occasionally. Lys told me that in the busy time Grant met her every two weeks, while in the less-busy time, only once a month in the group meetings. I also saw that they discussed current problems and progresses in the corridor, just on the way from the office to the laboratory or from coffee room to restroom.

Dealing with misunderstandings and flaws

Senior researchers focus on general ideas while juniors on technical details. This division of labour was generally believed by my informants as an ideal working mode, as the seniors were usually faster in catching the key points and main insights of a research topic than the juniors. When misunderstandings or research flaws are encountered, it is faster for seniors than juniors to check up every technical detail of data analyses and experiments and to correct flaws. For example Bob the senior physicist in 'BPS' repeatedly blamed to me that juniors made more mistakes than seniors.

However, the time spent on communication maybe shorter if a junior researcher becomes well trained. For example, Weber, a doctoral physicist junior research in Grant's team, told me that he was extremely naive when he started the doctoral program but in his last year of PhD study, he had developed new technologies on electronic microscopy. It took Grant, who was his senior, a lot of time to explain the basics in physics but when it came to a later stage of Weber's PhD, he did not need to know all the details and parameters for observing certain kinds of materials as these were all taken care of by Weber.

Thus it is fair to claim that the time of juniors spent for clarifying misunderstandings and correcting research flaws is higher than seniors when the juniors lacks experience. This gap can be shortened when juniors have fully developed their skills and knowledge.

Building up trust

In the 4S team, seniors need to pay much danger of hurting trust if one urges or even monitors the progress of other's work, which may not be avoidable during the collaboration due to the distinction of research cycle. It is because seniors are those who decide the directions of a joint project. If trust among seniors get hurt, the IDCT will crash down. For the same reason, in the 2S+2J teams, junior researchers are able to communicate and even push each other without worrying about the lost of trust. Meanwhile, in 2S+2J teams, as both seniors know that it is the juniors who really make the everyday progress, they will push their students rather than each other. The seniors are able to assign juniors specific problems to work on and get results without paying much attention on details (Stamp et al., 2015; Turner et al., 2015). Building trust via the division of labour happened in 2S+2J team seems to be an easier and more efficient one compared with learning everything by seniors.

Working on the same pace

In the 2S+2J teams, senior researchers are focusing on general ideas, juniors are engaged in the 'zip process' and keep the synchronization of work. Thus the time cost on jumping between general ideas and practical issues at the kick-off stage of the 4S teams is not necessary any more. In other words, to achieve the work synchronization as the benefit, the 4S teams need more time spending, thus is less efficient than the 2S+2J teams.

Bargaining on the authorship

Authorship on co-publications is an important form of academic outcomes. It is clear that compared with seniors, juniors have less sayings on the issue of authorship. Thus bargaining of authorship among four senior researchers would be more time costly than among two junior and two senior researchers.

In sum, in this part, through ethnographic fieldwork and comparison between two types of organisational structure, I've identified a number of interesting factors that are of decisive importance in determining the efficiency of an interdisciplinary collaboration. It could be argued that, if the participant juniors are well-trained, the benefits/costs of works and communications in the 2S+2J team is higher than in the 4S team, which ideally makes a 2S+2J team work more efficiently. Yet if with fresh-person junior researchers in an IDCT, it is extremely difficult to make such a decisive conclusion. However, these factors were of great importance to anyone who is interested in establishing an efficient collaboration team.

5.2 Effectiveness in interdisciplinary knowledge production

As one of, maybe the most important benefits of interdisciplinary collaborative efforts, the effectiveness of innovation is defined as 'a multi-stage process whereby organizations transform ideas into new/improved products, service or processes', namely, generating new knowledge or objects (Baregheh, Rowley, and Sambrook, 2009: 1334). Innovation discussed here involves two inter-related dimensions: the first is originality, and second is the effects of implementation (Lee, Walsh, and Wang, 2015), as original ideas 'become innovations only after they are implemented' (Gumula, 2018: 2). Indeed, blurring disciplinary boundaries inspires new ideas and perspectives and provides opportunists to employ old ideas into new knowledge systems (Uzzi and Spiro, 2005; Vojak, Price, and Griffin, 2010). Prior studies have been conducted to tease out the mechanics of innovation in scientific researches (Uzzi et al., 2013; Wu et al., 2019). For instance, from perspective of the content of knowledge, Uzzi and his colleagues (2013) found that innovative scientific articles were based on unusual combinations of prior researches. From perspective of the size of research teams, Wu and his colleagues (2019) claimed that small-size teams and big-size teams were functioning differently in the term of research effectiveness: the former produced more creative works than the latter, while the latter was better in gradually developing a research area. However, it still remains unclear that inside a small-size IDCT who (junior/senior researchers in which participant discipline) is possibly contributing on which part of the innovation.

Hardness of answering this question partially lies on the lacking of a proper method to qualify how creative and effective an idea can be in the working process of interdisciplinary knowledge production. A way of measuring novelty of a scientific work, developed by Uzzi and his colleagues (2013), relies on quantity and quality of published results of the teamwork, that is academic journal articles. Yet, the developing property of innovation, the so called multi-stage process, seems out of being considered in such kind of result-based parameters. Based on the semantic network model of creativity (Yu et al., 2016), I will in the second half of this chapter develop cognitive map analyses by formulating parameters that operationalise both creativity and implementation of innovation. Further, I examine the three IDCTs introduced in Chapter Four in order to find out how people contribute to the innovation of an IDC project.

5.2.1 How innovation is operated

Yu and his colleagues emphasised that 'creativity (their creativity is what we mean innovation here) contains novel ideas that are unrelated to existing knowledge' (2016: 269). However, information homogeneity (Granovetter, 1973) happens when dense connections among people are built in a interpersonal network because 1) people have already shared the similar information and 2) people have been such a clique that outsiders can hardly join in. In a similar vein, there will be limit opportunity of creating new ideas unless foreign concepts are successfully linked into this conceptual system. More connections to these foreign concepts is positively associated with the higher possibility of generating new ideas.

In the context of IDC, these barrier-broker ideas are usually coming from other disciplines. As alien knowledge, they are introduced into and made connections with a system of local disciplinary knowledge, then create new notions that are possibly inspired or combined by both side. In this vein, breakthroughs of the interdisciplinary project, that is the implementation of creative ideas, is essentially based on the utility of the network of the whole family consisting of these alien knowledge, local knowledge and 'new-born mix-blood' knowledge. Consequently, the more connections that are made among the whole family of concepts, higher possibility this process of disciplinary border-crossing practice produces innovative research results.

Thus I argue that a scientist's creativity in the interdisciplinary research depends on how much foreign concepts have been involved into his/her original disciplinary knowledge system. Whilst the implementation of the research is associated with how dense the family members of alien, local and 'mix-blood' knowledge are connected.

In more details, for each cognitive map, creativity can be presented by the parameter of coverage, namely the number of nodes with alien disciplinary concepts involved dividing to the number of nodes within their only home discipline. The higher this ratio is, the more this cognitive map, that is personal knowledge system, is influenced by the interdisciplinarity, which indicates higher opportunity of creativity.

Yu and his colleagues deployed the parameter of density of the semantic network to indicate the implementation of the knowledge system. We have used this parameter in Chapter Four. It signifies the extent to which each scientific notion is connected in a knowledge network. I argue that for cognitive maps, density perfectly represents the same idea. The distinction lies on various interpretations on what the parameter density implies. Compared with what have been discussed above, Yu and his colleagues claimed that it showed how people were focusing on specific groups of topics, which was not necessarily match the cases here. The reason lies on the variety of levels of conceptual expression for semantic networks; the meaning of one scientific concept may include or overlap with another. What I am focusing on the density of cognitive maps is how much the creative idea possibly influence, namely making connections with, the local knowledge conceptual system in order to make further progress of the academic research.

By plotting the coverage and density of each cognitive map in each IDCT at all stages, Figure 5.2–5.4 vividly illustrate how much creativity and implementation each team member has probably contributed to the research project. In these figures, nodes on the above-right of the plain, compared to those at other positions of the plain, signify that the researcher's work, according to his/her understandings, might be significantly innovative. Nodes on the above-left present those quite creative but less possible to be implemented, which are just the opposite to the those on the down-right. Nodes located on the down-left show that this researcher is potentially much less creative nor implemented than the rest.

It is noted that this way of measurement is only an indication of potential innovations. It does not serve as a proof of whether findings of the research conducted by each participant of an IDCT is innovative or not.

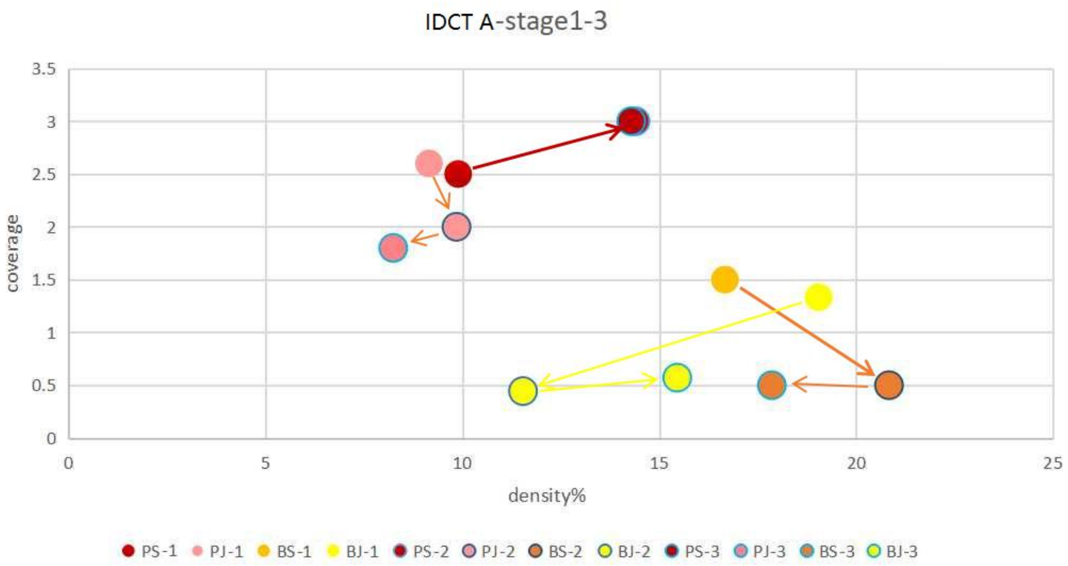

Figure 5.2 The contribution on innovation of all group members in IDCT A, the stage 1-3. Names of PS, PJ, BS, and BJ in IDCT A has been shown in the Table 4.1

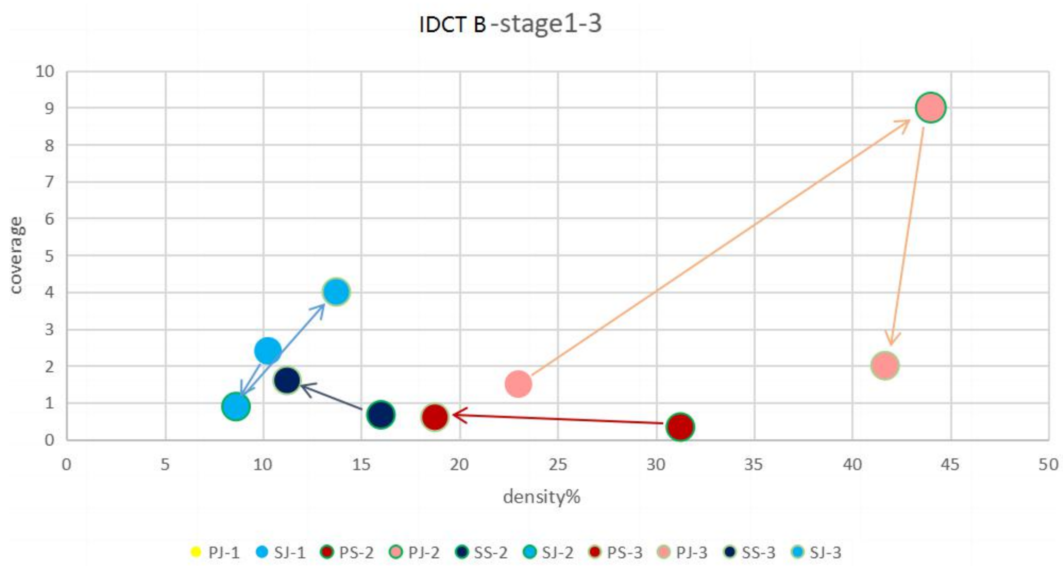

Figure 5.3 The contribution on innovation of all group members in IDCT B, the stage 1-3. Names of PS, PJ, SS and SJ in IDCT B has been shown in the Table 4.1

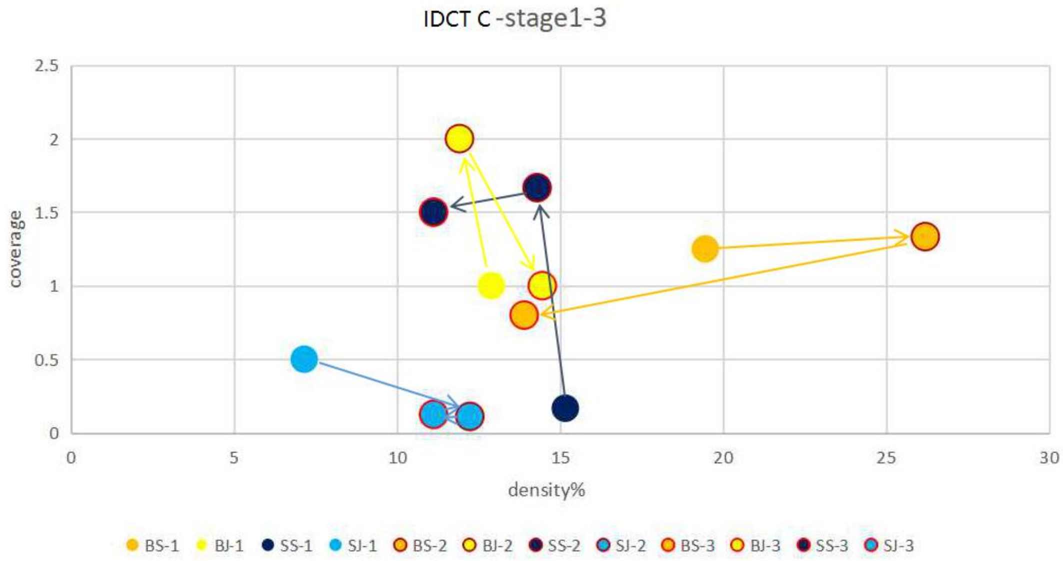

Figure 5.4 The contribution on innovation of all group members in IDCT C, the stage 1-3. Names of BS, BJ, SS and SJ in IDCT C has been shown in the Table 4.1

5.2.2 Distribution of contribution by disciplines

5.2.2.1 Is there any difference of innovation made by discipline?

Figure 5.2–5.4 depict a clear distinction on discipline from which people contribute to the innovation of an IDCT. In figure 5.2, all red nodes, which represent junior and senior physicists, are located on the up-left side of the plain, implying that they are taking care of creativity rather than implementation. In comparison, both biologists, shown by yellow nodes, are more focusing on the opposite, that is the implementation aspect of the their knowledge systems. Statisticians, who are often found locating on the down-left of their collaborators on the plain, seems less innovative than either biologists nor physicists.

What is illustrated by Figure 5.2–5.4 echoes the claims of both statisticians and physicists by saying '*we are not slaves of biologists*' (Will and Bob). According to above-shown analyses, statisticians and physicists are playing distinctive functions in innovation of the research project. For physicists, their creativity is possibly quite high because they have included many alien concepts from other disciplines. Yet, it seems that the implementation of these concepts might be low, meaning physicists are not so much connect alien concepts into the local knowledge system in order to create a dense new knowledge system. One proper explanation may rely on their having succeeded in triggering physics research questions they satisfied. Another one may be that at the same time they need quite a lot of alien knowledge to establish a new theory, especially those describing physics laws in biology systems. That is why my informants bare a mixed attitude of appreciation and half complains on the fact that '*when people collaborate with physicists, they need to talk and talk until they understand everything*' (Chris). On the contrary, statisticians neither need so much information from alien disciplines nor need to embed their knowledge into foreign knowledge systems so much. It seems like they really need less, compared to physicists, to establish a new algorithm. Lys once told me that she had repeatedly told Will that they were studying skeleton of bone cells but every time he talked about some other kind of cells from such as muscles and tissues but not from bones. Apparently it does not matter what kind of cells it is for statisticians because they only care about the way to model the trajectory of cell's movement.

5.2.2.2 Is there any distinction of innovation made by the hierarchy?

The hierarchy position, being senior or junior researcher, matters as well. Yet it is not as some of my junior researcher informants have claimed; senior researchers are not always more innovative than who they hire. In fact, as shown in figure 5.2–5.4, two modes of division of contribution on innovation between junior and senior researchers can be found.

The first mode is named as functional distribution of innovation like statisticians in IDCT B and biologists in IDCT C. In both cases, it is the juniors who take care of creativity and seniors of implementation. The junior researchers in this innovation mode, always being considered as young people with opener minds, are easier to deal with new ideas from other disciplines. In comparison, their seniors, who have been more familiar with and somehow constrained by their well established disciplinary expertise and perspectives, are more experienced in figuring out the way of integrating new ideas with the whole knowledge system.

The second mode is called as totalised distribution of innovation, as one of the senior and junior researcher is considered more creative and implementable than the other. In most of the cases, like Bob and Chris in IDCT A and Will in IDCT C, the seniors are more advanced. The exception includes Lys in IDCT B, when the junior is far more innovative than her supervisor, Chris. One of the possible reason would lie on the rather close interactions between Lys and her statistician collaborator, which made their ideas deeply involved into each other's knowledge system and meanwhile densely integrated together.

However, when talking about innovation during the interview, Lys won't believe herself as the group member with highest contribution on innovation: '*My supervisor knows most of my experiments in details, thought probably not by heart. But he knows...[when talking about her collaborators from the statistics department] I do not know the skills as good as them. They do not know how to do the experiments and do know how to do analysis quite well.*' In general, indeed, her expertise is merely on experiment designs and data collection. She confirmed that it was the senior researchers who got the whole ideas of the research project, including ideas about what kind of experiment was to be conducted.

I argue that the reason of this contradictory lies on the distinction between the nature of two kinds of materials: cognitive maps show what people are thinking in minds, while interviews reveal what people are talking about. Not necessarily, Lys talked about innovation in a general and long-time scale; indeed, it might be those senior researchers who contributed more on the innovation of the whole project. But at the exact stages she was conducting cognitive maps with me, her in practice was more innovative than all her group members. Thus the findings by cognitive mapping analysis claimed above introduce the temporal but not general contribution of innovation of each group members. In this vein, the combination of cognitive map analysis and interviews make a more complete view of the distribution of contribution in IDC projects.

5.2.3 Implementations and future studies

Apparently, due to a limited data set, it is not possible to enumerate all modes of innovation in IDCTs. However, via these three plots, we have found out that not all people are equally innovative in IDC projects; the degree of innovation various among IDCT members. It is interesting if modes of division of labour discussed in Chapter Four are reviewed by comparing modes of innovation. Contents of work, either general direction of the project or practical details, which are associated with position in the academic hierarchy, seem to be indifferent with contribution of innovation. In other words, even though seniors may set up the whole topic and structure of the project, practical works on data or technical issues may still be the most innovative part of the research.

Even though a structural interpretation on this division of contribution of innovation has not been found through this paragraph, the approach developed here provides an opportunity to calculate quantitatively who contribute on what. A future study is supposed to link this measurement to the final evaluation on contribution, that is, authorship and intellectual ownership; who takes what credits in the collaborative effort? Answering this question is able to help further understand how work process of knowledge production influence the accumulation of academic capital; what is the nature of this incentive system running in the contemporary academia.

Chapter Six

Conclusion

How is knowledge interacted among scientists in interdisciplinary collaborative teams (IDCT)? So far, this dissertation has argued that the interaction of knowledge relies on interactions between structured mental networks of notions running in scientists' minds. Overlapping of these networks may suggest mutual understandings achieved by scientists, which also lay the base of the formation of IDCTs; structural properties depicting interrelationship of these networks reveal how discipline and hierarchical position of scientists in an IDCT influence their research interdependence as well as to what degree and kind of innovation a scientist aims for.

This final chapter provides a systematic conclusion of the whole dissertation. The first section revisits three lines of arguments claimed in this dissertation. Developed from the empirical findings in this dissertation are insights on a new kind of cognitive structure–interpersonal structure relationship, to be elaborated in section two. Policy comments that are derived from findings of this dissertation are given in section three. The last section limitations and future studies are discussed.

6.1 Key arguments in a glimpse

Prior science and technology studies (STS) have tried to understand the process of knowledge production, namely how data, arguments and research ideas are constructed and used to form up a systematic understanding of social or natural phenomena, which are bracketed as scientific knowledge. Further developed from those works, this research teases out how knowledge is interacted between people's minds through daily interpersonal communications in the context of interdisciplinary collaboration. As the main theme of this dissertation, knowledge interaction refers to the process in which scientific knowledge from scientific researchers' minds is exchanged, integrated and co-produced during interpersonal communication in various academic settings, like academic discussions, supervisions, seminars, group meetings, conferences. Knowledge that is examined here is not what people write in a textbook. It is neither the collective knowledge that is accepted and shared by a specific academic community, nor abstract knowledge in the term of facts or laws as results of scientific research. Rather, it is the understanding that an individual scientist learns from the literature, textbooks, her/his colleagues and results from conducting empirical investigations, running a simulation or processing an experiment. It also contains infrastructures one uses to test hypotheses and to organise teamwork such as individual time schedules and research plans. Thus what is discussed in this dissertation is a procedural and flowing process of how people conceptualise their collaboration and they deal with various challenges in different stages of their interdisciplinary collaboration.

Three lines of arguments have been deployed to further reveal multiple perspectives of these interactions.

The first line of arguments in this dissertation offers a methodological innovation. Deploying the method set of cognitive mapping, interview and participant observation, this dissertation has opened the 'black box' of knowledge interaction, namely has emphasised and visualised the structure and dynamics of personalised knowledge networks. In doing so, this dissertation has revealed how these networks affect organisational structures of interdisciplinary research teams. A cognitive map, drawn by a scientist as my informant during a semi-structured interview, is a network of interconnected research concepts, methods, equipment, data and events. The nodes and links in this network are changing when the informant is communicating with other collaborators. These kinds of changes, which can be presented by continuously collecting new cognitive maps, include adding new nodes, deleting old ones, replacing new meaning or extra details on old nodes and establishing or deleting meaning or directions of links between nodes.

In Chapter Two, we have discussed various elements of cognitive maps. With these elements, cognitive maps are able to illustrate 'cognitive aspect of scientist' activities' (Whitley, 1970: 61) thus to reveal 'the internal cognitive nature and form of science' (Whitley, 1970: 61), which have been long pointed out as a main theme STS should have aimed to but have been limited teased out. One of the important functions of the method of cognitive mapping, as the most innovative methodological endeavour in this dissertation, is to visualise and understand the structure of shared knowledge between scientists as boundary objects (Star and Griesemer, 1989). More than that, these maps further illustrate how boundary objects are linked with the temporal existence of knowledge systems in each researcher's mind. In this vein, the whole information of boundary objects, which includes structures that are not only 'sufficiently common to ensure minimum identity in terms of intersection' but also 'sufficiently flexible to adapt to the specific needs and constraints of each of these worlds' (Trompette and Vinck, 2009: 6), is visualised. The exact part of shared knowledge can be seen through a comparison between two cognitive maps, rather than through a summary of interviews made by sociological and anthropological interviewers (like DuRussel and Derry, 2005).

The second line of arguments centers on the cognitive mechanics of knowledge interaction in IDCTs, namely in the cognitive level, how scientists come up with the possibility of an interdisciplinary collaboration. In particular, cognitive mechanics is summarised by the answers of the following four questions: what is shared knowledge, how the shared knowledge is established, how much is the minimum required extend of shared knowledge and how shared knowledge lasts with the development of an IDCT.

First, shared knowledge in this dissertation requires not only the identical mental representation of a certain scientific notion, which has been defined as a boundary object. Rather, scientific notions as the shared knowledge should be understood and interpreted in the same meaning by a pair of scientists who share it. In this vein, the shared knowledge can be regarded as a specific type of boundary object. Also, compared to Collins' and his colleagues' rather strict definition of this concept (2007, 2019), which indicates only physical objects, this dissertation employs a wider meaning that includes also abstract thoughts and notions.

Second, according to findings of Chapter Three, a full establishment of the shared knowledge should go through two processes. The first process comprises the contextualisation of the research topics and related concepts. In the second process, demands and offers are presented and integrated in order to form up consensuses on concrete research topics, shared notions and a research agenda, which sometimes is came up with by emergence.

Third, a minimum extent of sharing of knowledge exists between seniors in an IDCT and is distinct according to various patterns of the collaboration: the theory-method pattern and technical pattern (Dai and Boos, 2017, 2019). In the former pattern, one of the team members provides theoretical ideas and interpretations while the other serves research methods for data collection and analyses, require a structure of shared knowledge, namely not only the same notions in cognitive maps but also the same links between these notions. In the latter pattern, people from two disciplines just share technical issues like chemicals, a microscopy or data, need to share only limited notion or notions that are isolated.

When considering an IDCT with both senior researchers and juniors, it is not necessary for each pair of team members fulfill the minimum extent of knowledge sharing. Rather, the required extent of shared knowledge between disciplinary groups, namely between the senior and junior researchers in one discipline and those from the other, would be enough for the base of an IDCT.

Further, it is worth noting that in an IDCT with two-layer hierarchy (consisting of juniors and seniors) the collaborative patterns still work for disciplinary groups if the senior and the junior in the same discipline are considered as a disciplinary group. Due to the fact that the division of labour has cut the research procedure of one discipline into different sections that are assigned as sub-tasks to the seniors and juniors, the collaborative pattern analyses cannot be deployed on individual. Having not been elaborated in former chapters, this argument can be further exemplified by the IDCT C of 'BPS' group. In general, the biology side followed theory-initiated research procedure, but statistics side took data-initiated research procedure. Meanwhile, their research goals were different. Chris and Leo's goal, as introduced in Chapter One, was to find out the mechanics of the mitotic wave. However, Ling told me excitedly that never before there was an algorithm that could analyse trajectories in an irregular surface. But data from mitotic wave of fruit fly embryo provided a perfect opportunity to study this algorithm, for which he had tried all potential models he had learned. Albert told me that he was reading articles analysing flying trajectories of migratory birds by vector analyses, which he could apply to analyse similar trajectories on embryo's surface.

Thus on the level of disciplinary groups, it can be claimed that the biologists collaborated with statisticians in a theory-method IDC pattern. On the individual level, collaborative procedures were divided into two parts: a theory-method pattern loop between Leo and Albert who were dealing with data, and a comparison process made between Chris who was taking care of general ideas, hypotheses and models and Ling who works through the whole process of statistics. Still, because Chris does not go through the whole biology research procedure, the collaborative pattern between him and Ling is unanalysable.

Forth, due to the instability of boundary objects, maintaining such kinds of shared knowledge cost time and energy. If the above mentioned limitation of sharing of knowledge is not fulfilled, the IDCT will break in the invisible cognitive level then in the visible interpersonal level. In addition, with the development of knowledge co-production, shared knowledge boundary objects change in terms of structures and contents. These changes are affected by personal benefit-cost calculation, chaos in group management, emergent affairs or even holidays. How to keep them always 'alive' is still a research question to be studied in the future.

The third line of argument is about interpersonal mechanics of knowledge integration, namely how scientists work in practice interdependently as a joint research team. The interpersonal mechanics can be derived from answers to the following four questions: how to define research interdependence among team members in IDC? How people divide their labour in an IDCT? How team hierarchy and disciplines to which scientists belong influence the research interdependence? And how this division of labour affects the efficiency and innovation of an IDCT?

First, the concept of research interdependence describes in the interpersonal level the ways people rely on each other in terms of research content (Whitley, 2000) and work flows (Thompson, 1967). The former is conceptualised as content interdependence and the latter task interdependence.

There are two main differences between Whitley's definition and the one used in this dissertation: first, the group of people considered by his concept regards to an academic community, normally a specific scientific field; but I consider people in one single interdisciplinary research team, which is on a much smaller scale than the former. Second, my informants do not necessarily quote each other's publications, as results of studies, because they rely on each other's works to make small progresses before the accumulation of all these small progresses leads to a publishable milestone result. In this vein, the kind of interdependence discussed in this dissertation is a rather micro-level one.

In general, interdependence between tasks has been demonstrated not to be relevant between people who work on these tasks (Puranam et al., 2012). Yet by examining 'who does what in what sequence', Chapter Four teases out a clear division of labour between senior and junior researchers, which signifies a stratified and dynamical distribution of workloads among them.

Second, an IDCT in natural sciences involves not only seniors, who are usually the lab-leaders (Knorr-Cetina, 1999), but also juniors, who are students or post-docs paid and supervised by the seniors. It is found that the seniors and the juniors have different responsibilities. The junior researchers conduct practical and technical works asynchronously and they establish strong links between their knowledge systems. By contrast, seniors take care of general ideas and the construction of research projects synchronously. In terms of the extent of knowledge shard by two members of the same IDCT, it is found that two seniors of two disciplines share less amount of knowledge about the IDC project than two juniors of the same two disciplines. In addition, one senior has the least overlapping of his/her knowledge deployed in the IDC project with that of the junior of the same discipline.

This division of labour is made due to institutional and personal reasons. In general, juniors, most of which are Ph.D candidates, are not allowed to apply for their own projects. In addition, compared to senior researchers, juniors are less experienced in conducing researches and master less knowledge about both overview and details of the project. Consequently most of the juniors start their first classes of research by reading literature of prior studies and learning to operate equipment in laboratories. But this division of labour is not fixed all the time. When the junior get more experience in research, they extend their visions, accumulate enough knowledge and spark their own insights of potential directions of the project. In the 'BPS' group, IDCT B, Will the senior statistician gradually ask Alan the junior to hand over the whole project, only with himself being reported if only any progress was made. In this vein, the seniors contain no mere lab-leaders like Knorr-Cetina (1999) has defined.

Third, it is argued in Chapter Four that the content, strength of connection and rhythm of interdependence are distinctive by various positions in the research teams and partially intellectual structures of various disciplines. Whilst the intellectual structures vary by disciplines, which has been found playing an important role in mono-disciplinary research teams, effect no longer the rhythm of task interdependence of an IDCT, but only the strength of knowledge connections between collaborators.

Modes of knowledge interaction happened in daily academic lives in laboratories help explain why interdependence happens like above-mentioned. This dissertation claims three interactive modes in an IDCT: the networking mode between senior researchers contributes one of the main reasons of their mobility; the plantation mode between a pair of senior and junior in the same discipline reveals part of the nature of supervision; while the mode of zip process between juniors suggests how a research project is made progress in practice.

Forth, the division of labour also contributes to enhancing the efficiency of IDCTs, if participate juniors are well-trained. A qualitative benefit-cost calculation based on the transaction cost theory in Chapter Five has suggested a framework of analysis on this issue.

In addition, though work interdependently, IDCT members contribute distinctively the innovation of the research project. Two innovation modes have been identified and illustrated in this dissertation. The first mode is the functional distribution of innovation, in which juniors focus on the creativity and seniors on implementation. The second is the totalised distribution of innovation that the creativity and implementation of one of the senior and junior researcher remains higher than the other. By plotting coverage and density of each cognitive map, it is found that both the team hierarchy and discipline strongly influence the patterns of innovation, even though only the former affects how people divide their works.

In sum, by deploying the method of cognitive mapping this dissertation for the first time reveals in the cognitive level the details of formation, development and function of shared knowledge among knowledge systems of IDC participants. In addition, ways of interacting and extends of integrating these knowledge systems that vary by discipline and hierarchy position of scientists in an IDCT lead to a certain way of division of labour in an IDCT in the interpersonal level. Till now, findings of this dissertation have unfolded concrete understandings, actions and strategies of scientists in IDCTs thus illustrate processes of interactions of knowledge in both cognitive and interpersonal levels (see figure 1.3). Following the cognition orientation of STS claimed by Whitley, these findings have not only answered the question of 'what are scientists thinking and doing in practice in research projects', the problem that bothered the founding fathers of STS and their great followers (they are but not limited to Mannheim, Merton, Kuhn, Whitley, Knorr-Cetina and Pinch), but also enrich existing advices for sustaining an IDCT.

Before we go into these advices, there is still one important question to answer: what is the relationship between the cognitive knowledge sharing and interpersonal research interdependence?

6.2 The problem of embeddedness

The above-mentioned discussions on cognitive and interpersonal mechanics of knowledge interactions touch one of the central, general and old questions of the study of science and scientific knowledge: what is the relationship between the knowledge structures people bear in mind and the interpersonal structures people establish as a research team?

In order to clarify this relationship, it is necessary to review the concept of embeddedness (in 6.2.3), which is THE base of social networks theories and related analyses. Originally, this concept is deployed to describe a particular kind of relationship between economic actions and interpersonal networks, in which the former has been found processed on the base of the latter (Granovetter, 1985). Interpersonal relationships have greatly influenced the trust, friendship, common experience and identity, which play crucial roles on making business contracts between firms and strategies of collaboration. Similarly, in prior section, I have elaborated that connections and synchronous of cognitive structures of scientists are the basis of interdisciplinary collaborative research actions. The former is a necessary but not a sufficient condition of the latter. Thus in this section, I will illustrate that the concept of embeddedness can be deployed to describe not only relationships between social relationships and economic actions, but also cognitive relationships and collaborative networks.

6.2.1 Social attributes of science

Social attributes of science, such as the existence of scientific communities, organisational structure of a research team and the division of scientific labour, have been long emphasised by sociology of science, sociology of scientific knowledge (SSK), and science and technology studies (STS). Against pure, objective 'Natural Law' that was believed independent to the human beings, social attributes of knowledge have been found playing crucial roles in the process of constructing knowledge. In Chapter One and Two, we have introduced and compared among the ideas of Mannheim, Merton, Whitley, Knorr-Cetina and Pinch's. Considering scientists belonging to occupational groups, studies of above-mentioned researchers, I claim, are established on a shared hypothesis: a systematic disciplinary set of scientific knowledge is institutionalised (Whitley, 1974) to be shared by a field or a community of scientists. A tacit deduction can be followed as since scientists coming from the same scientific field or community share a common epistemic ground, they can understand each other easily well. Indeed, the field and community is where and how people present their social and cultural attributes: they are assumed to share the same research paradigm (Kuhn, 1962), theoretical backgrounds, methods of research and epistemic culture, which made them as an unique group. In this vein, people belonging to a certain scientific field are naturally believed baring a cognitive consensus with others in the same field. That is why it is able to be claimed that type of researches with intellectual structure (Whitley, 1978) and epistemic culture (Knorr-Cetina, 1999) is associated with social organisations of scientific work.

That said, what has been ignored by this community-based point of view is the widely existing cognitive distinctions between almost every pair of scientists. Personal cognition does matters in small-size IDCTs investigated in this dissertation. For instance, scientists from the same discipline may deploy totally different ways of organising a research team. Yann the senior physicist in the 'CSP' group insisted on working all physics works by himself in the 'Leadership–Followership project', even though it was so easy for him to get access to student assistants and doctoral students working for him. Compared with Yann, the two senior physicists in the 'BPS' group carefully divided pieces of works and assigned the technical parts to their students hired to work for them. As another example, scientists from various disciplines and with distinctive intellectual structures may deploy the same team hierarchy. In Chapter Four, we have demonstrated that all three teams made up of physicists, statisticians and biologists followed the same interactive modes.

6.2.2 A network perspective

What makes the research presented in this dissertation different, as shown in Chapter Four, is that I take a network perspective (Simmel, 1922) rather than considering scientists in social groups as well as treating knowledge as categories. Against Whitley and Knorr-Cetina's arguments on type of researches or epistemic cultures in certain scientific fields, I argue that when examining practical interdisciplinary research projects, it is not necessary for scientists from the same research field also share the same epistemic properties because they are influenced by their own cognition histories formed up by their collaborators from different hierarchical positions, various alien fields and most importantly their personalised unique experiences of scientific practice. Here I do not deny the possibility of the existence of such kind of epistemic knowledge shared within a research field. But what I want to emphasise is that the complex, practical and dynamics contexts that an individual scientist is encountering in research projects is playing a far more important role than prior studies have expected. In addition, not only interpersonal relationships are considered as networks, knowledge is also an individual-based network of notions: everyone has his/her own understandings and way of construct understandings on the project one is working on. It is worthy of noting that I am not claiming that the intellectual structure and epistemic culture are no longer influential in interdisciplinary collaborative efforts. Rather, they do matter in patterns of innovation.

6.2.3 Embeddedness

This dissertation claims that interdisciplinary collaborative interpersonal networks are embedded into the cognitive networks of notions that are related to the project people are working on. This embeddedness relationship is further elaborated by the following three points:

First, as elaborated in this dissertation, various ways of producing knowledge and scientific knowledge itself are essentially running in people's networked-structured minds; the cognition serves as a processor and a base for the whole process of interdisciplinary scientific knowledge production. With the help of cognitive mapping, this networked-structured individual-varied cognition of research notions have been clearly illustrated and compared. Knowledge makes sense to scientists if only they have translated the knowledge into their own cognition, namely understand each concept and link between those concepts by integrating them into their existed knowledge systems.

Second, without a mutual consensus of the cognition on certain notions that participant scientists deploy in joint scientific activities, there is no way of conducting the collaborative works with establishing only interpersonal trust or other kinds of relationships. The 'CSP' group spent three years to establish this base. But without the required minimum extent of knowledge sharing fulfilled, the research team working on the 'Leadership–Followership', even having been established and been running for a whole semester, still fell apart.

Third, the cognitive connections, namely shared knowledge, offer opportunities to create new interpersonal links. Connecting to the knowledge systems of someone before involving him/her in the project has been considered by my informants as an important principle when establishment of a new research project or handover of the research job take place. The need of this cognitive connection for a research position is perfectly illustrated by Chris, the senior biologist in IDCT A and IDCT C:

'*In the annual workshop of DFG (Deutsche Forschungsgemeinschaft) I presented the work of my research group. I also went to hear reports of other projects, where I met my current* *collaborator Ling. He was presenting an interesting statistic model, which I think would help to analyse the image data of nuclei of the embryo. Then we discussed a lot about our data and successfully applied for a new joint research project. We see how many research positions are available by the funding. Then we post advertisement on our website. For example we need to hire a doctoral student who has deep understanding on the knowledge of development biology and high skills in biological experiments...In this way we built up this research group.*'

The knowledge and skills required in Chris's advertisement are to provide possibilities of cognitive connections between a new Ph.D student and Chris as the team leader. Apparently, Chris prefers to establish work relationships with a junior research who has accepted professional training in development biology, which has in a certain degree guaranteed that they share the same scientific notions in biology. In other words, work relationship between a senior and a junior has to be established on, namely embedded into, connections of knowledge systems.

An additional example helps to further elaborate the relationships between connecting knowledge systems and establishing collaborative relationships. This is a case of the handover of research works. In particular, when a junior researcher leaves the position, a follow-up junior researcher is required. But by illustrating the case of David and Watson in IDCTA, I argue that only when the successor have established cognitive connections with all research partners of the predecessor can the handover take place successfully. Metaphorically, this handover process is as hard as replacing gears with new ones that have not been well meshed. To re-match the new gear into its position costs time and energy. The failure of this re-matching may shut down entirely the zip process so that stop the whole project.

The junior physicist in IDCT A who collaborated with David was Watson, a post-doc. In the middle of the project, Watson left for industry, which made troubles to David. '*Watson and I cooperated well' said David, 'we gave each other feedback as soon as we can. I gave him images from my experiments, and he in days sent me results of data analyses...if there was any problem, we contact with each other via phone calls... Thus we made progresses very fast.*' Due to long period of working together, David told me that they had well understood on each other's research and needs. It is a pity that I did not manage to meet Watson, but I had to agree with David because of the confirmations on his opinion by both Chris and Bob.

Before Watson left, Micheal, as a research assistant who used to help Leo (the junior biologist in IDCT C) running biology experiments and who also took part in David's collaboration with Watson, was the best person to take the vacancy. Besides, he had enthusiasm in learn programming skills, which is highly demanded by the work of Watson's position. So Chris and Bob offered this research position to Micheal, and Michael took it. After Michael took over, he made a lot of effort to make sense of Watson's coding. '*The coding was not formalized. Some parameters were not marked so that it was hard to understand what they were represented...Maybe only Watson himself knew.*' Michael complained. As he had already fully understood what his biologist collaborator was working on, the data-analyses of the project was only halted for around several weeks to adjust the personnel change. Figure 4.6 illustrates what Michael was thinking about his project. He not only listed many biology details about David's work, but also displayed his work in the project into a block: after 'image segmentation', he implies 'co-variance' and 'correlation', two ways of 'statistic analysis', to conduct 'data analysis' in order to build up the 'theoretical model'. In this way, Michael and David finally managed to meet each other's needs so that successfully run the zip progress again.

After Micheal's graduation, his successor, Frank, did not manage to build these cognitive connections because Frank was interested in 'Drosophila hearing systems', a new research topic that might be related to what Micheal and David were working on. As a result, Frank, who supposed to be hired working in IDCT A, had to be assigned to another project of his supervisor (Bob). Thus IDCT A has to halt again until Bob hired a new junior researcher who was able to take the place of Micheal.

Graduations cause a cleavage of networked cognitive systems. Yet only with cognitive connections built up again, can an IDC project run and move forward. It is worthy of noticing, however, that having established cognitive connections cannot guarantee the formation of a fixed organisational structure. Otherwise Yann would not have been affected negatively by his reluctance of investing more time into the potential collaboration given his pragmatic strategy toward publication. In this vein, I claim that in IDCTs the cognitive connection between networks of notions is a necessary but not a sufficient condition of establishing the organisational structure as a research team. And it presents what the hidden meaning of the embeddedness.

One may be curious that the interaction of knowledge, as one of the research actions between scientists, should be embedded into the network of interpersonal relations, if a simple analogy is made between the IDC context and the sociology of economics (Granovetter, 1985). Yet it is not.

The question Granovetter met was to clarify the relationship between economic actions and social structures. Before Granovetter, economics believed that economic actions were taken by under-socialised rational players pursuing for maximizing benefits or over-socialised social regulations. He emphasised the significance of the networked interpersonal relationships, such as trust, strong tie, weak tie among others at work during economic exchange progresses. As he claimed, the economic actions are 'embedded into concrete and ongoing system of social relations' (1985: 487).

What makes this argument 'conversed', I argue, is the difference of personal cognition that has been neither barely realised nor carefully studied in social network theories followed Granovetter's school. It is not surprising that people need to understand each other in order to establish interpersonal relationships for trade or joint research project. Uzzi (1997) operationalised embeddedness as a set of logic constructing motivations and expectations. Such kind of logic is not to selfishly pursue short-turn benefits but to cultivate long-turn collaborative relationships. However, how to establish long-turn collaborative relationships is a question deeply rooted in specific social and cultural contexts. Just like Zelizer (1989) has pointed out, even money, one of the classical objects human society created in order to calculate heterogeneous values of goods in the form of neutral numbers, is unavoidably baring various social and cultural meanings. To be more specific, she argues that the names, shapes, ways of use and even quantity of money may be different because of various symbolic meaning systems of money particular groups of people are living with. For instance, in ancient China, dowry is supposed to support the living and position of the wife in a new established family, but not to be used by the husband; in modern society, 'pocket money' is a small amount of money given to a child; in last century in America, house wives got 'butter money' or 'egg money' rather than 'salary' or 'wage'; and in some society, 'dirty money', though a great amount of it, can not be used for trading. Scientific knowledge, to a certain extent, is not neutral as well. Rather, it has shown an apparent distinction by academic social status and disciplinary cultures. For instance, general topics and directions of the project are considered by senior researchers; while practical and technical knowledge is deployed and produced by juniors.

Biologists care for certain kinds of proteins with particular functions in the developing process of cells; while statisticians prefer to abstract positions and trajectories of (whatever) cells by numbers.

What if two traders coming from different cultures holding various meanings on the transaction activities and money want to trade something? Misunderstandings happen, and, in most cases, they cause problems to the transaction progress. This is exactly the situation 'CSP' group faced at the beginning. People from different disciplines held distinct expertise and goals of potential collaborations. Before seminars by fall, 2012, they had conducted tens of group meetings, shared dozens of dinners. They knew each other as colleagues bearing will of collaboration. Maybe they did not totally trust each other. But there must be some couples of them who did, at least who treated each other as a friend. Weak ties seemed had long been established and maintained among group members. That said, a simple fact had been omitted by the quick abstraction of social network studies: ties are fake and transferring probably wrong messages when people have not developed a mutual understanding of each other's cultural and social contexts. That is why their collaboration had not been established during 2010-2012 with a network of interpersonal relationship in which people were able to embedded their interactions of knowledge, namely their 'trades'.

As a special field, the 'economic' actions in the IDC context are knowledge interaction. Scientists need to establish understandings on each other's knowledge system, just like merchants on each other's meaning systems of goods and money. Cognition thus is one of the key bases people are able to meet, to communicate, and to build trust and attitudes on others. In this vein, it is not a conversed conclusion that social networks are embedded into cognitive networks. Rather, it may be universal to people in academic, economic and many other fields. An individual person is no mere a social individual, but also a cognitive one.

6.3 Practical Guidance on IDC practice

Suppose another group of people facing similar situation to the 'CSP' group. What shall this dissertation suggest? Suppose another group like 'BPS' tries to establish their collaboration and make their communication smoothly, what tips can my findings give?

Numerous comments and protocols have been claimed for sustaining interdisciplinary collaborative efforts (e.g: Klein, 2005; Defila et al., 2006; Bendix et al., 2017). These comments are sub-tasks that guide IDC participants to conduct research jointly, tips of organising teams and resources and policy advice that may sustain potential IDCs. However, due to the lack of examination on the cognitive level of interdisciplinary research practices, existing comments are not able to illustrate those sub-tasks and tips concretely enough. For instance, most of prior studies suggest scientists to start their collaborations with forming up concrete research targets and shared research questions. But how to clarify research targets and questions specifically is still not so apparent for every scientists. Neither how much knowledge sharing is necessary for building mutual understandings on which the collaboration is able to run is not mentioned. Compared to the prior researches, findings in this dissertation are able to provide hand-on practice guidance on interdisciplinary collaboration in various ways.

From the cognitive level, three tips point out necessary tasks. Without any of them unaccomplished scientists are not able to establish an IDCT.

First, the epistemic process of contextualisation has to be shown by each side of IDC participants, unless they really understand what each other is saying. The point is to clarify tacit knowledge in each discipline: after all, what one has taken for granted is not recognised by others. By showing a concrete case, followed by grabbing parts of the phenomena or features of phenomena into abstract concepts and asking a question upon them, one should make each other understood how people in his/her field think of a research question, what kind of question is meaningful in the field, what are the practical backgrounds and meanings of specific concepts when one talks about them and what is their degree of abstraction. At this point, what Steve the computer scientists elaborated upon trust in Chapter Three is a perfect case.

Second, the key to fulfill knowledge integration is to be aware of what I call as 'four Whats': what one requires from potential collaborators, what one can really get from them, what one is expected to provide from collaborators, and what one is able to provide. In short, participants know each other's abilities and needs. Definitely it is not always an easy job. In most of the cases, the idea of an IDC project starts when one is simply thinking of asking people from other disciplines to collect or analyse the data: computer scientists wanted sociologists to provide parameters so that they could operationalise them into data collections; biologists needed physicists and statisticians to analyse the data they had collected; statisticians wanted biologists and physicists to provide new data so that they could develop new measurement theory, followed by new algorithms; social psychologists needed computer scientists to simulate their experiments and physicists to build a theoretical model...Yet these rather 'simple' requirements always do not work because facing the same set of data, people from different disciplines hold various degree of abstraction, generate distinctive concepts and ask different questions in different contexts. However, by claiming what one hope his/her collaborators to contribute on the joint project, one has to also consider from his/her collaborator's side. And indeed, this process of translation of 'gains' is required by both sides.

Third, it will also be helpful if IDC participants consider what kind of collaborative pattern they are employing: theory-method pattern or technical pattern. In this way, scientist are able to expect the extend of knowledge sharing required by a certain pattern. Time and patience have to be given to collaborative partners because one always wants to set up a research question in their own field, which takes time, different duration of time. Otherwise one fell him/herself being treated as a slave or being hired as a labour to assist his/her 'master' scientists.

From the interpersonal level, two tips derived from findings of this dissertation help to run an IDCT smoothly and a research laboratory innovatively.

First, from the perspective of running a project, according to Chapter Four, frequency and content of meetings for senior and junior researchers may be different, except of group meetings that all take participant. Even though tasks have been distributed and assigned thought division of labour, to keep perspective rhythm of meetings between researchers is still important. In particular, between juniors, regular meetings need to be set every week or two for updating mutual requirements and for exchanging practical pieces of advice that are specific to collaborating team members' expertise, materials and techniques and to the work progress. For seniors, to keep themselves found is necessary especially for moments when there is a problem or progress. In a word, a smooth communication is the key for IDC efforts when a division of labour happens.

Second, from the perspective of a laboratory in which several research projects are running in parallel, the division of labour is presented by combining these research projects of both theory-method pattern and technical patter in a smart way. Indeed, according to Dai and Boos's suggestion (2019), a proper combination of them–often dependent upon disciplinary or interdisciplinary backgrounds of laboratory members and their academic abilities–enables a highly efficient, synergistic deployment of knowledge resources. Heads of laboratories are encouraged to diversify the methodical and technological tool box of the entire lab according to projects of the technical pattern run by various teams of the laboratory, which in turn will support or even generate theoretical breakthroughs by those of the theory-method pattern. In this way, a strong platform can be set up by technologies developed and exchanged through the network of technical interdisciplinary collaborative projects to sustain other projects in the laboratory, whilst innovative and concrete topics are formed through interfaces between disciplines established by theory-method interdisciplinary collaborations. With new topics inspired and the right technologies at hand, a laboratory will be able to effectively engage in innovative projects and support interdisciplinary collaboration teams more efficiently.

6.4 Limitations and Future Directions of Research

There are certain both theoretical and methodological shortages in this dissertation, which is to be improved in the future studies.

The first theoretical shortage lies on the lack of examination on the institutional level of interdisciplinary collaborations. In fact, this dissertation has tried to avoid examinations on this level by controlling physical locations of all selected IDCTs. Yet different departments in the same university may still hold various attitudes, supportive, neutral or negative, to faculty members' dedication to conducting researches across disciplinary boundaries. These attitudes may have made differences on scientists' strategies of investment of time and person-power in the interdisciplinary efforts. In this vein, for people from distinctive disciplinary departments, benefits and costs may be considered in a more complicated ways than what Chapter Five have teased out. In this dissertation, these differences derived from institutional rules and regulations have not been discussed.

Second, results of IDC efforts, that is publications, have not been discussed in this dissertation. There are reasons to hypothesis the division of labour in knowledge interaction and co-production influence the property claiming for publications, which is shown by the order of authorship. In the future studies, a simple yet critical issue of 'who takes what credits in the collaborative effort' needs to be tackled with based on investigations on the co-production process of knowledge. Questions as followed can be asked: how do participating members of a research project negotiate academic co-publications as part of their interdisciplinary collaboration efforts? In particular, how do they evaluate individual contributions in a collaborative project and decide the sequence of authors and contact persons in co-publications? What are the social and legal constructions of intellectual property in IDC projects? To what extent the authorship in co-publications reflects the ownership of co-produced knowledge? These questions will lead studies on IDCTs back to the context of academic capitalism and marketisation and will help to reveal the nature of the reproduction of academic capitals in sense of academic capitalism.

Third, this dissertation did not pay much attention on how cognitive structures probably also influence the quality of interpersonal networks and relationships, such as interpersonal characters and team identity, which are crucial to the succeed of an interdisciplinary collaborative effort

(Bendix et al., 2017; Defila et al., 2006). These questions may be answered by future studies based on this dissertation.

This dissertation has also methodological shortages. First, the fact that I am conducting a long-term case-based research on IDCS certainly result in the limitation of the number and width of the scope of cases under study, which constrains my research from revealing far more general mechanics of knowledge interaction. As well, discussions are made under a German context. Different phenomena and mechanics may be found from cases of other countries. Thus a said research project investigating more cases of richer categories will help both generalise and further elaborate phenomenal findings of this dissertation. However, with this small number of cases, I have tried to show multiple phases with various methods. That is why Chapter Three gives a qualitative ethnographic account, and Chapter Four gives a structural sociological analysis and Chapter Five is more of a quantitative discussion. Even though, I admit that there are still huge amount of valuable details remaining hidden under my statements on overall landscape of the cases under my investigation. Also, my conclusions are constrained by the university I conducted my fieldwork, English as working language in laboratories and the small number of investigated team members. What this dissertation tells are merely a part of various patterns, reasons and tips I am able to learn from my informants.

Second, taking care of minds when discussing social structures or institutions, as this dissertation has claimed, suggests potentials breakthrough on the synthesis of different networks, especially between cognitive network, personal network and organizational network According to the embeddedness discussed in Chapter Six, what are happening on the cognitive level, the process of knowledge construction and interaction in minds, reveal vary detailed reasons of how people establish, cut or maintain certain social relations, attitudes and role playing. Compared to social construction analysis, cognitive analysis illustrates structures of what people are thinking, according to which a quantitative analysis can be conducted to reveal dynamics of knowledge construction that is associated with social constructions. In this vein, this work makes the first step in arguing that graphic cognitive analysis has the potential to provide other than social networks dynamics, a strong tool to understand the epistemic dynamics.

Tips suggested by this dissertation have a certain practical limitation, for they are not to guaranteed that IDC efforts will be successfully established and conducted. In fact, nothing can make this strong commitment. These tips are only lighthouses, helping scientists to clarify what is happening during communications with people from other fields and what they have to consider as a direction to step forward. Also, these tips will only be put into practice if scientists in IDCTs are aware of their problems of knowledge interactions in IDC mentioned in this dissertation and are willing to solve these problems. Otherwise these tips will not be valued nor be applied in order to establish and maintain a successful IDCT.

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Declaration

My opportunity to take part in this doctoral procedure was not commercially brokered. In particular, I have not sought out the services of any organisation that provides advisors for the completion of dissertations or would fulfil the duties incumbent upon me with respect to examination-related achievements in whole or in part.

I hereby declare that I have prepared the dissertation submitted, Opening the Black Box: Cognitive and Interpersonal Mechanics of Knowledge Interactions in Interdisciplinary Collaborative Teams, independently an without any unauthorised assistance. I have not accepted any external aid with or without remuneration, nor will I do so in the future. I did not use any aids or writings other than those I have listed. All passages taken either verbatim or in adapted form from other authors are indicated as such.

The dissertation I hereby submit has not yet been submitted in the context of any other examination procedure.

Furthermore, I am aware that any falsehood regarding the present declaration shall exclude me from admission to the doctoral examination and/or shall later lead to termination of the doctoral procedure or to revocation of the title I may receive.